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ABSTRACT

The report presents a grammar capable of analyzing the process of production of electricity in modular elements for different power-supply systems, defined using semantic and formal categories. In this way it becomes possible to individuate similarities and differences in the process of production of electricity, and then measure and compare “apples” with “apples” and “oranges” with “oranges”.
For instance, when comparing the various unit operations of the process of production of electricity with nuclear energy to the analogous unit operations of the process of production of fossil energy, we see that the various phases of the process are the same. The only difference is related to characteristics of the process associated with the generation of heat which are completely different in the two systems. As a matter of facts, the performance of the production of electricity from nuclear energy can be studied, by comparing the biophysical costs associated with the different unit operations taking place in nuclear and fossil power plants when generating process heat or net electricity. By adopting this approach, it becomes possible to compare the performance of the two power-supply systems by comparing their relative biophysical requirements for the phases that both nuclear energy power plants and fossil energy power plants have in common: (i) mining; (ii) refining/enriching; (iii) generating heat/electricity; (iv) handling the pollution/radioactive wastes.
This report presents the evaluation of the biophysical requirements for the two power-supply systems: nuclear energy and fossil energy. In particular, the report focuses on the following requirements: (i) electricity; (ii) fossil-fuels, (iii) labor; and (iv) materials.

Keywords: Nuclear Energy, Nuclear Power, Nuclear Fuel Cycle, Light Water Reactor (LWR), Fossil Energy, Integrated Gasification Combined Cycle (IGCC), Electricity, Life-Cycle Assessment (LCA), Biophysical Economics, Bioeconomics

Contents

List of Abbreviations

ANDRA	French Radioactive Waste Management Agency *(Agence Nationale pour la Gestion des Déchets Radioactifs)*
BWR	boiling water reactor
CEA	French Atomic Energy Commission *(Commissariat à l'Energie Atomique)*
CCS	carbon capture and storage
CO2	carbon dioxide
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPR	Evolutionary Power Reactor (formerly European Pressurized Reactor)
HLW	high level waste
IAEA	International Atomic Energy Agency
IGCC	integrated gasification combined cycle
ILW	intermediate level waste
ITER	International Thermonuclear (fusion) Experimental Reactor
LLW	low level waste
LWR	light water reactor
MIT	Massachusetts Institute of Technology
MOX	mixed oxide
NEI	U.S. Nuclear Energy Institute
NRC	U.S. Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
PC	pulverized coal
PES	primary energy sources
Pu	plutonium
PW	paid work sector
PWR	pressurized water reactor
SNF	spent nuclear fuel
tce	ton of coal equivalent
toe	ton of oil equivalent
U	uranium
Udep	depleted uranium
Urep	reprocessed uranium
UO2rep	reprocessed uranium fuel
VLLW	very low level waste
WCI	World Coal Institute

Units

h	hour
J	joule
m^3	cubic meter
t	metric ton (10^3 kg)
W_{el} or We	watt electric
Wh_{el}	watt-hour electric
Wd_{th}	watt-day thermal
SWU	separative work unit

SI unit prefixes

k	kilo (-10^3)
M	mega (-10^6)
G	giga (-10^9)
T	tera (-10^{12})
P	peta (-10^{15})

1. Introduction

Since the analogous unit operations of the electricity generation process are essentially the same between nuclear energy and fossil energy, the performance of these two power-supply systems can be studied by comparing the biophysical costs associated with those unit operations when generating process heat or net electricity.

In this report, I provide the data necessary to compare the performance of nuclear energy and fossil energy in making electricity. The report includes:

(a) Introduction of the grammar for comparing the performance of power-supply systems, and nuclear energy vs. fossil energy in particular (Section 2);
(b) Selection of the baseline cases and evaluation of their parameters (Section 3);
(c) Evaluation of the material balances (Section 4);
(d) Evaluation of the biophysical requirements using the grammar (Section 5).

2. Grammar applied to the analysis of energy systems

2.1 Introducing the concept of grammar

The assessment of the difference in quality between different energy sources has to be based on a quantitative analysis capable of handling *the inherent ambiguity associated with the concept of energy* (Giampietro and Sorman, 2012). Then, the quantities of energy considered as relevant for the assessment can only be measured and aggregated after having agreed on a pre-analytical definition of a *grammar* characterizing a given set of finite transformations. A grammar consists in a set of expected relations linking semantic categories (the different energy forms used in the process) and formal categories (the relative quantification) according to a given set of production rules (for a more detailed description see Giampietro et al., 2011, Chap. 6). Because of its ability to establish an agreed relation between the chosen semantic (perception of the issues) and the chosen formalization (representation of the issue) a grammar guarantees a shared meaning for the numbers developed within the grammar. That is, by using a grammar about which there is an agreement on its relevance, it becomes possible to characterize the performance of primary energy sources based on a quantitative assessment—considering different biophysical requirements in relation to the different energy forms involved in the process of energy transformations.

2.2 Defining a frame for assessing the quality of PES

The process of production of electricity (an energy carrier) starting from a given PES (e.g. nuclear, coal, hydro) requires a series of different unit operations. Therefore, in order to be able to compare different processes of production of energy carriers (EC) in relation to their performance and relative "costs" it is important to individuate and define the set of tasks and relative compartments in charge for these unit operations to be used for the assessment. This translates into the pre-analytical choice of a grammar defining: (i) the semantic categories used in the representation of the process (primary energy sources, energy carriers, set of conversions, labor input, etc.); (ii) the formalization of these categories into quantitative assessments; and (iii) the production rules determining relevant quantitative results. For example, when dealing with the assessment of the quality of nuclear energy in the production of electricity, the grammar individuates the set of energy transformations across different energy forms that take place within each power-supply system.

2.3 Examples of grammar of power-supply systems

In Figure 1, a few examples of grammar are provided to contextualize the peculiarity of the production of electricity with nuclear energy in relation to other PES.

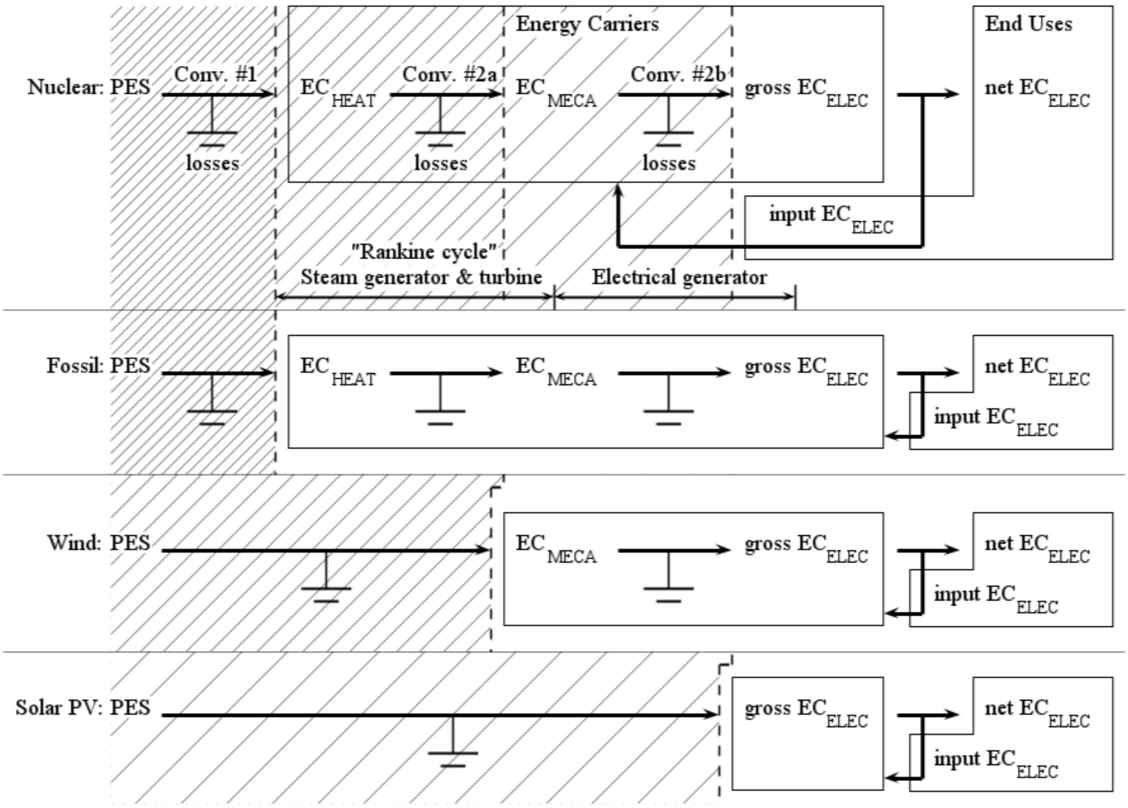

Figure 1: Examples of grammar of PES for the production of electricity

For instance, the following set of energy transformations (or conversions) can be identified for the production of electricity using nuclear energy:

- Conversion #1: PES to EC_{HEAT}
- Conversion #2a: EC_{HEAT} to EC_{MECA}
- Conversion #2b: EC_{MECA} to gross EC_{ELEC}
- Conversion #3: gross EC_{ELEC} to net EC_{ELEC} (End Uses)

In this grammar related to nuclear energy in the production of electricity, process heat and mechanical energy are introduced as EC although they are not directly delivered to society (End Uses). Moreover, conversion #3 does not strictly correspond to an energy transformation but rather to a loss of EC due to the "energy for energy" dissipative part.

2.4 Comparison between nuclear energy and fossil energy

A comparison based on our grammar clearly indicates that nuclear energy and fossil energy present a striking similarity in the overall structure of energy transformations. In fact, the various phases of the process of production of electricity are the same. The only difference is the set of energy forms and energy transformations used to generate "process heat" (conversion #1 in Figure 1). Nevertheless, the two energy systems can present some quantitative differences in the other energy conversions (mostly in conversions #2a and #3), so that they must be included in the study.

In Figure 2, we present a flow-fund scheme[1] comparing the various phases of the nuclear energy process for the production of electricity to the analogous phases of the process with fossil energy. Those phases of the process of production represent the semantic categories used to carry out the quantitative assessment.

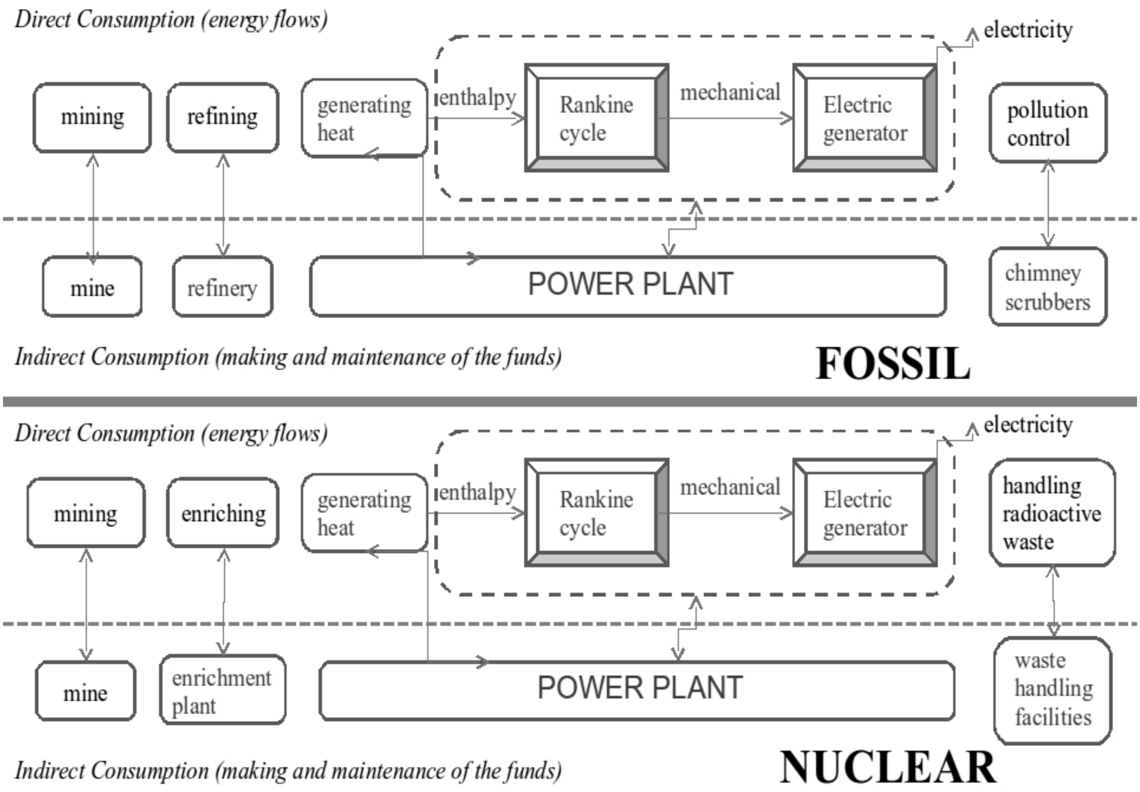

Figure 2: Comparison of the process of electricity generation – Nuclear energy vs. Fossil energy

The remainder of this report characterizes the baseline cases of both power-supply systems (Section 3), and provides the evaluation of the biophysical requirements of the two systems using this grammar (Section 4).

3. Baseline cases

3.1 General discussion on the selection of the baseline cases

Two baseline cases are considered for each one of the two energy systems that are studied leading to a total of four cases identified throughout the study as follows:

1 This report adopts a biophysical representation of the metabolism of socioeconomic systems through Georgescu-Roegen's (1971) flow-fund theoretical model. In this model, *flows* (e.g. energy inputs, material flows) refer to elements disappearing and/or appearing over the duration of the representation (time horizon of the analysis), while *funds* (e.g. capital, people) refer to agents that are responsible for energy transformations and are able to preserve their identity over the duration of the representation (for a more detailed description see Giampietro et al., 2011, Chap. 7).

- Case 1: Nuclear energy – Light Water Reactor (LWR) power plant;
- Case 2: Nuclear energy – LWR power plant with reprocessing;
- Case 3: Fossil energy – Integrated Gasification Combined Cycle (IGCC) power plant;
- Case 4: Fossil energy – IGCC power plant with Carbon Capture and Storage (CCS).

The selection of those two couples of baseline cases for the comparison between advanced technologies of fossil energy and nuclear energy systems for the production of electricity is mainly motivated by (1) the availability of the selected technology (Cases 1 and 3); and (2) the pace at which new designs can be deployed and become a representative technology in the worldwide electricity generation from either nuclear or fossil energy (Cases 2 and 4).

On that respect, advanced designs of fossil energy power plants including CO2 capture (Case 4) are considered as an available technology (or soon to be at large scale) whose deployment would be much faster than the future generation of nuclear power plants (generation IV) which technology is not yet available and whose deployment would require many decades (if they are to be deployed) before becoming a significant technology in the nuclear energy sector.

The same applies for *fission* versus *fusion*. Indeed, only nuclear *fission* energy is considered here as it corresponds to the only application currently performed from thermonuclear physics for industrial purposes (excluding medical applications)—mainly in the production of electricity[2]. Although, research about potential commercial application from nuclear *fusion* energy is achieving some progress as the experimental stage is expected to start in the mid-term—through the ITER project announced to be in operation by 2019—followed by a demonstration stage—the future DEMO prototype power plant—announced to be operational by 2040 (ITER Organization, 2011), we cannot realistically expect nuclear fusion to become a significant (primary) energy source for supplying electricity (an energy carrier) over the 21st century. Indeed, even the commercial application of nuclear fusion energy before the end of this century can be questioned as (i) there are still fundamental research questions that have not been answered yet by the community of nuclear fusion scientists—such as the experimental impossibility to reach a self-sufficient tritium breeding process necessary for fusion power plant operation (Dittmar, 2012); (ii) there is a systemic problem when scaling-up a new nuclear power program mainly due to the different degree of complexity between academic-reactor operations and an operational-reactor fleet—which has been the case during the first nuclear fission energy era (Bupp and Derian, 1978; Yang, 2009; Grubler, 2010); and (iii) the deployment of fusion nuclear power plants would imply a nuclear-fuel cycle transition which requires from 50 to 100 years to happen (Kazimi et al., 2011) which would be further delayed if a new fleet of Generation IV reactors is to be deployed in the mean time, or simply because of the existing technological lock-in that affects nuclear technology (Arthur, 1989; Cowan, 1990). For those reasons, nuclear fission energy is very likely to remain the only nuclear energy source over the 21st century and maybe beyond into the future. On that respect, expectations about the use of nuclear fusion energy appear to be out of (time) scale given the fact that energy supply issues would have to be addressed before this potential primary energy source becomes available.

2 The use of nuclear fission energy for the production of industrial process heat is not within the scope of this study although it represents on possible application of the same nuclear technology.

As far as the nuclear fuel cycle, according to an MIT study the LWR partly closed fuel cycle consisting in reprocessing the plutonium and uranium, implies a reduction of the enriched uranium fuel demand of about 15% and 10% respectively (Kazimi et al., 2011). According to the same study, the spent used nuclear fuel (SNF) can only be reprocessed one or two times (Kazimi et al., 2011). The partly closed fuel cycle is therefore currently used only as an experiment both in France and in the UK. Its potential large scale deployment would require between 50 to 100 years (Kazimi et al., 2011) and since it also raises proliferation concerns it does not represent today a significant fuel cycle option. Nevertheless, it has been considered in this study (Case 2) in order to evaluate the effects of the reprocessing phase on the performance of the overall nuclear energy process.

3.2 Description of the baseline cases used for the comparison

3.2.1 Case 1: Nuclear energy (LWR power plant)

For the nuclear energy production process, I consider the same baseline case of a typical 1300MWe power plant with a light water reactor (LWR) as used by Lenzen (2008) along with a once-through nuclear fuel cycle meaning that no reprocessing is being considered during the whole process.

LWRs—including pressurized water reactors (PWR) and boiling water reactors (BWR)—represent about 90% of the worldwide installed capacity of nuclear power plants connected to the grid (CEA, 2010), while most new plants are on average 1300MWe—from 1000MWe to 1600MWe. The load factor of 79%—shown on Table 1—corresponds to the annual average load factor of all currently operating LWRs in the world (CEA, 2010). The burn-up value corresponds to the amount of thermal energy extracted from initial nuclear fuel in the reactor, expressed in gigawatt-days per metric ton of uranium (GWd_{th}/t_U). It depends on the nuclear fuel re-load of the reactor—$45GWd_{th}/t_U$ corresponding to the average value for LWRs (Lenzen, 2008). The uranium fuel consumption of $25t_U/y$ comes from the mass balance evaluation detailed later in this section. This is consistent with the average values of $20t_U/GWe$ per year (Kazimi et al., 2011) corresponding to about $26t_U/y$ for the selected baseline case. It shall be mentioned that the burn-up value depends only on the nuclear reactor technology, not on the uranium ore quality. Indeed, the burn-up value is imposed by the frequency at which uranium fuel is re-loaded into the reactor while uranium fuel is adapted to the reactor type. The quality of uranium ore (grade or natural enrichment) then plays a role in the enrichment phase—the lower the uranium grade, the more enrichment effort required as detailed in Section 4—and therefore ultimately influences the fuel consumption of the nuclear power plant.

Such a defined nuclear power plant generates about 100,000TJ of process heat (or enthalpy, in our case of an isobar process) and about $9,000GWh_{el}$ of (gross) electricity per year.

Parameter	Value	Unit	Source
Burn-up	45	GWd_{th}/t_U	Lenzen, 2008
Uranium fuel consum.	25	t_U/y	*see Table 5*
Process heat generated	97 600	TJ/y	
Plant capacity	1300	MW_{el}	Lenzen, 2008
Load factor	79%	(World av. for LWR)	after CEA, 2010
Electricity generated	9000	GWh_{el}/y (output)	
Rankine cycle efficiency (gross)	33%		

Table 1: Parameters of Case 1

3.2.2 Case 2: Nuclear energy (LWR power plant with reprocessing)

Case 2 differs from Case 1 by including a reprocessing phase into the nuclear energy production process. The reprocessing phase consists in the partial recycling of the used fuel (uranium) and products of the fission reactions (plutonium), as well as in the reprocessing of the depleted uranium (Udep) which operations lead to reducing the consumption of natural uranium. This phase is further detailed in Section 4.2. Table 2 presents the parameters of the baseline Case 2 which are essentially the same as Case 1 since the reactor technology remains the same. The only difference is that the nuclear energy production system is not only burning enriched natural uranium but also reprocessed fuel—i.e. mixed oxide fuel (MOX) and reprocessed uranium (UO2rep)—so that the annual heated material (HM) consumption remains equal to 25t/y as for Case 1.

Parameter	Value	Unit	Source
Burn-up	45	GWd_{th}/t_U	Lenzen, 2008
Heated material consum.	25	t_{HM}/y	*see Table 6*
Process heat generated	97 500	TJ/y	
Plant capacity	1300	MW_{el}	Lenzen, 2008
Load factor	79%	(World av. for LWR)	after CEA, 2010
Electricity generated	9000	GWh_{el}/y (output)	
Rankine cycle efficiency (gross)	33%		

Table 2: Parameters of Case 2

3.2.3 Case 3: Fossil energy (IGCC power plant)

For the fossil energy production process, a 480MWe Integrated Gasification Combined

Cycle (IGCC) power plant using coal has been selected as the baseline case of this study. The coal-based IGCC technology, presented in Figure 5, corresponds to one of the new advanced designs of fossil-fueled power plants discussed in a study from the MIT (Katzer et al., 2007) and whose latest baseline designs have been assessed by the U.S. Department of Energy (US DOE/NETL, 2010a). The IGCC technology consists in turning the coal into gas in order to remove impurities before it is combusted, improving the overall efficiency of the power plant.

Contrary to nuclear energy, the burn-up (or heating value) of a fossil-fueled power plant does not depend on the selected technology but rather on the type of coal being mined (e.g. bituminous, lignite, etc.). As a matter of facts, the heating value of 26GJ/t—shown in Table 3—has been calculated according to the proportion of each coal type being exploited in recoverable reserves (see Table 7). The load factor is taken equal to 80% (US DOE/NETL, 2010a) leading to a coal consumption equal to 1.45Mt/y (after US DOE/NETL, 2010a). The Rankine cycle efficiency is considered equal to about 40% (after US DOE/NETL, 2010a), which shows some improvements in the efficiency of the latest IGCC designs (38% in Katzer et al., 2007). On that respect, it shall be noted that the Rankine cycle efficiencies have been evaluated by removing the electricity requirements of the "Mining" and "Handling waste" phases for which electricity requirements will be accounted separately in Section 5. The difference of efficiencies between Case 3 and 4 is therefore due to lower efficiencies of the same processes—i.e. the lower efficiency of Case 4 only translates the losses in the same equipments when the system contains a CCS technology and does not include the electricity requirements that go into the equipments of the CCS itself.

Such a defined fossil-fueled energy power plant generates about 37,100TJ of process heat and about 4,200GWh$_{el}$ of (gross) electricity per year. The corresponding power plant capacity is then equal to 480MWe.

Parameter	Value	Unit	Source
Heating value	26	GJ/t$_{coal}$	*see Table 7*
Coal consum.	1.45	Mt$_{coal}$/y (av.)	after US DOE/NETL, 2010a
Process heat generated	37 100	TJ/y	
Rankine cycle efficiency	40.4% (av.)		after US DOE/NETL, 2010a
Electricity generated	4200	GWh$_{el}$/y (output)	
Load factor	80%		US DOE/NETL, 2010a
Plant capacity	480	MW$_{el}$	

Table 3: Parameters of Case 3

3.2.4 Case 4: Fossil energy (IGCC power plant with CCS) – 90% of CO2 capturing

Case 4 differs from Case 3 by adding a carbon capture and storage (CCS) technology which reduces the CO2 emissions of the power plant by 90%. The IGCC technology is one of the leading candidates for electricity production with CO2 capture (Katzer et al., 2007; Rubin et al., 2007; US DOE/NETL, 2010a), which justifies our baseline case of IGCC+CCS. Although those new designs are still under development—especially the CCS technology included in this Case 4—they represent the next generation of fossil-fueled power plants and are already being deployed in some places.

The CCS technology requires a certain amount of process heat—depending on the amount of CO2 being captured—mainly due to the gas-compression needed before injecting the carbon into the ground (see Figure 5) so that the Rankine cycle efficiency drops from 40% down to about 34% (after US DOE/NETL, 2010a) as shown in Table 4. In order to compensate part of the loss of efficiency, the coal consumption is increased to 1.52Mt/y (after US DOE/NETL, 2010a). The (gross) process heat of such a defined fossil-fueled power plant is equal to about 39,100TJ per year which difference with Case 3 is only due to the higher annual coal consumption. Then, the net process heat (36,500TJ/y) generated by the selected fossil-fueled power plant can directly be derived from the loss of Rankine cycle efficiency. The corresponding power plant capacity is then equal to 420MWe.

Parameter	Value	Unit	Source
Heating value	26	GJ/t_{coal}	*see Table 8*
Coal consum.	1.52	Mt_{coal}/y (av.)	after US DOE/NETL, 2010a
Process heat generated	39 100	TJ/y (output)	
Rankine cycle efficiency	40.4%	(av. w/o CCS)	after US DOE/NETL, 2010a
	33.7%	(av. w/ CCS)	after US DOE/NETL, 2010a
Process heat generated	36 500	TJ/y (net)	
Electricity generated	3700	GWh_{el}/y (output)	
Load factor	80%		US DOE/NETL, 2010a
Plant capacity	420	MW_{el}	

Table 4: Parameters of Case 4

4. Evaluation of the material balances

In order to evaluate the different biophysical requirements for the four cases of the report, the annual material balance of each production process has been performed. Each material balance includes the different phases related to the fuel in all its successive forms—from the mining of ore to the handling of waste.

The mass balance evaluation is the most delicate step when studying nuclear energy (Cases 1 and 2) because (1) it requires making assumptions for several variables during each one of the different phases; and (2) there are non-linear relationships between the values taken by certain variables. In addition, the mass balance for those cases can be very sensible to the variables as discussed in Section 5.5.

For each case of nuclear energy, a figure presents the material balance of the baseline case considered showing the different phases using the grammar presented in Section 2. Values shown in the figures are detailed in the corresponding tables.

4.1 Case 1: Nuclear energy (LWR power plant)

Figure 3 presents in details the parts inside the whole process. In particular, the figure shows the three main phases of the process—“Mining”, “Enriching”, and “Handling waste”—according to the grammar detailed in Section 2. For each one of those phases, some sub-phases are presented in hexagons allowing to reach the level of details necessary to evaluate the biophysical requirements of the overall system.

Figure 3—as well as Figure 4—uses the energy systems language first proposed by H.T. Odum (1971) as a common denominator expressing all the flows and processes together in order to understand a whole system and the full interaction of the parts (Brown, 2004). The elements in those figures have the following meanings:

- Rectangles with a semicircle on the right represent elements transforming low-quality energy flows under control interactions to high-quality flows (*producer*) —corresponding here to the power plant (reactor).
- Rectangles with an arrow on the sides represent interactive intersections (*interactions*) between two different flows (energy forms).
- Circles represent the low-quality energy in its natural environment (*source*). This source corresponds to the primary energy source (PES) directly used by the energy system, meaning that it does not include other PES indirectly used through the consumption of other energy carriers (EC) such as oil and coal. PES is not produced by the energy system. It is therefore important to track its consumption, since it maps onto emissions and rate of stock depletion, a problem that affects all non-renewable resources—not only fossil energy sources (oil, coal and gas) but also mineral energy sources such as natural uranium.
- Triangles with a semicircle on the bottom represent the energy storage compartments of the system (*tanks*). Although those storage compartments do not perform any energy transformation, they do consume different EC for the maintenance of the flows and funds. In the case of the nuclear energy system, those compartments correspond to the handling of waste (storage and disposal).
- Earth symbols represent energy losses (*sinks*) corresponding here to the material flows that go out of the system considered in the study because they do not fall under any phase anymore. In the case of nuclear energy, waste with low levels of radioactivity (LLW after storage and VLLW) go into the environment and do not require any further management efforts. Nevertheless, the sinks are important to be identified in order to maintain the mass balance of the whole process in equilibrium. On that respect it shall be noted that the mass balance equilibrium is only ensured for uranium material flows (t_U). Indeed, secondary products that go in and out the process during the various front-end phases (“Mining” and “Enriching”) are not considered in the material flows so that the making and maintenance efforts (*funds*) of those *flows* are not included in the study.

  Note: Although Figure 3 shows that parts of the LLW/VLLW are considered as sinks, most of the radioactive waste coming from the different phases have to be handled (stored and/or disposed) which requires additional biophysical requirements.

Internal interactions between the elements in the figures are represented in the following ways:

- Black lines are flows of PES in their various forms from the "Mining" phase to the "Generating power" phase;
- Dotted lines are flows of waste (HLW, ILW and LLW) going to the last phase ("Handling waste") and thus exiting the flow path going to the reactor. It is important to identify those flows because they imply significant biophysical requirements due to their high amounts.

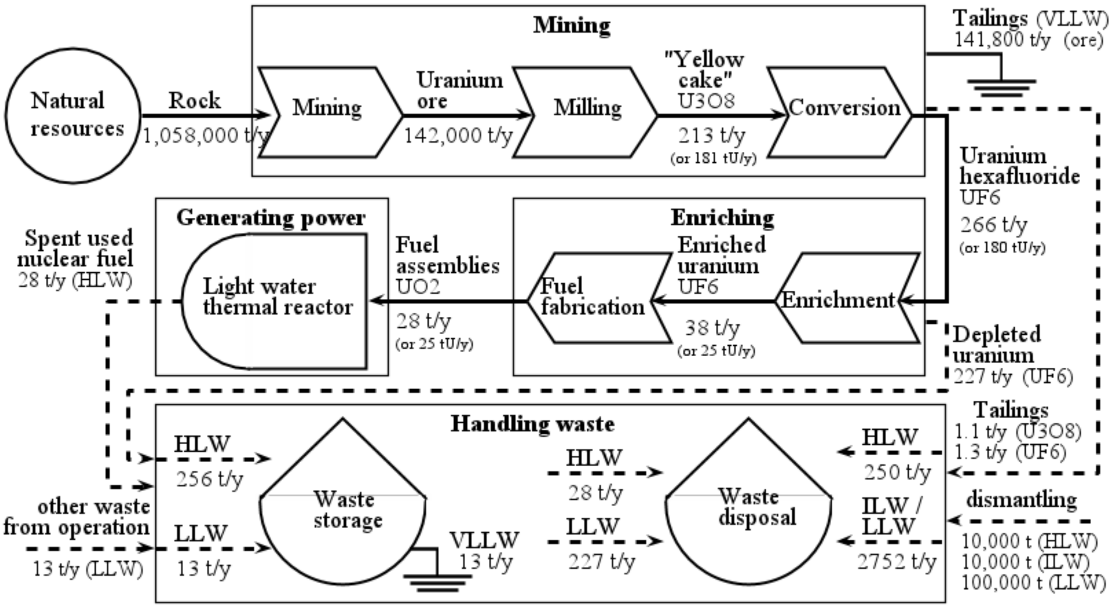

Figure 3: Mass balance of Case 1 (once-through nuclear fuel cycle)

Table 5 presents the calculations of the material balance of Case 1. In this table the following assumptions are considered:

- The overburden and waste rock which has to be removed to get access to the uranium ore in conventional uranium mines depends on the type of mines. Waste-to-ore ratio generally ranges from 20:1 to 1:1 for underground mines (with an average ratio of about 9:1) and from 5:1 to 1:1 for surface mining (US EPA, 2006). The average value of 7:1 has been evaluated based on the worldwide distribution of mining methods used to extract natural uranium (Lenzen, 2008). It shall be noted that since those waste are stored as waste piles generally close to the mining site, they do not enter into the material flows after the first front-end phase (mining).
- The ore grade—i.e. the content of natural uranium (U3O8 or "yellow cake" obtained after milling) in the ore extracted—varies significantly depending on the mines. The value of 0.15% U3O8 considered in this report corresponds to the baseline value of Lenzen's (2008) study.
- The recovery rate for uranium mining is expressed as a function of ore grade (% U3O8) as shown in Figure A.1 of the appendixes. The lower the ore grade, the less uranium is recoverable from the reserves. Storm van Leeuwen and Smith's regression (Ref. [30] in Lenzen, 2008) is shown in the figure with a trend line equation equal to:

$$f(x)=0.1241*\ln(x)+1.7465 \quad \text{with} \quad R^2=0.9617$$

The trend line shows a better accuracy for lower values of ore grade (x < 0.1%-U3O8) with a slight divergence above this value which does not significantly affect the results since the ore grade value considered remains in the low range.

- The losses of materials during the milling, conversion and fuel fabrication processes are taken from Lenzen's (2008) study.
- As explained in Section 3.2.1, I consider the same baseline case as used by Lenzen (2008). As a matter of facts, the assays (feed, tails and product) as well as the enrichment method distribution are taken from Lenzen's study.
- The mass balance of the uranium enrichment process has been evaluated adapting the calculator developed by the WISE Uranium Project (WISE, 2009a). This calculation can only be performed if one of the following four variables is known: enrichment effort, feed assay, tails assay or product enriched. When evaluating the mass balance, the last three last variables are not known. However, the characteristics of the reactor is known and so does its annual enrichment effort required. In the case of a LWR of 1GWe capacity, the annual enrichment effort—i.e. the separative work necessary in order to enrich the natural uranium up to the U-235 concentration required by the reactor—is about 120,000SWU (Hore-Lacy, 2004). Since, the enrichment effort is not a linear function of the reactor capacity, I stayed with this value for the study although the reactor capacity is 1.3GWe which is slightly conservative (lower enrichment effort than in reality) and represents the most critical assumption of the mass balance evaluation as all other variables indirectly depend on the value set for the enrichment effort. Results of the mass balance evaluation for the enrichment process are shown in Table A.1 of the appendixes.
- The amount of various operation and dismantling waste materials are taken from Lenzen's study (2008).
- The lifetime of the power plant is used to evaluate the annual flows of waste coming from the dismantling process. In Lenzen (2008), the lifetime of the LWR baseline case is set to 35 years. However, lifetime of power plants can be longer than 35 years when extended beyond their initial design. In the report, the lifetime is set to 40 years corresponding to the high end for generation II reactors. This assumption is conservative as it leads to flatten the flows of waste.
- There are various types of materials that have to be handled by being stored and/or disposed depending on their respective levels of radioactivity which vary in time. The fact that radioactivity decays in time implies that some waste can be temporarily stored without necessarily being disposed later. In this report, mining and milling tailings are considered being directly disposed as LLW without storage (NRC, 2011a); spent *depleted* nuclear fuel[3] is stored as HLW and then disposed as LLW after deconversion (NRC, 2011b); and spent *used* nuclear fuel (SNF) is stored and then disposed as HLW. The other waste from operation are stored as LLW until radioactivity has decayed away and can be disposed of as ordinary trash, or until amounts are large enough for shipment to a LLW disposal site in containers (NRC, 2011c). In the report, I consider no disposal after storage, which is a conservative assumption since it reduces the quantities of waste being handled. Last, waste coming from the dismantling process are directly disposed as either HLW, ILW or LLW.

3 The NRC uses the term of spent nuclear fuel making the difference between spent *depleted* nuclear fuel and spent *used* nuclear fuel. In the study, spent nuclear fuel (or SNF) when cited alone should be understood as being the spent *used* nuclear fuel.

Note: Numbers shown between brackets in Table 5 correspond to the waste flows represented by the dotted lines in Figure 3.

Phase	Parameter	Value	Unit	Source
(1) Mining	**Rock mined**	**1 058 000**	**t_{ROCK}/y**	
	Mining method	30%	open pit	Lenzen, 2008
		38%	ground excavation	Lenzen, 2008
		21%	in situ leaching	Lenzen, 2008
		11%	by-product of other mining	Lenzen, 2008
	Waste to ore ratio	9:1	Underground mining	US EPA, 2006
		3:1	Surface mining	US EPA, 2006
		7:1	(av.)	
	Recovery rate (yield)	94%		adapted from Lenzen, 2008
	Waste rock	**(916 000)**	**t_{ROCK}/y**	
	Ore recovered	**142 000**	**t_{ORE}/y**	
	Tailings	**(141 800)**	**t_{ORE}/y**	
	Ore grade	0.045%	U3O8 – Low (Australia)	Lenzen, 2008
		0.15%	U3O8 – baseline	Lenzen, 2008
		8%	U3O8 – High (Canada)	Lenzen, 2008
	Milling loss	0.5%		Lenzen, 2008
	Milling	**213**	**t_{U3O8}/y**	
		181	***t_U/y***	
	Tailings	**(1.1)**	**t_{U3O8}/y**	
	Conversion loss	0.5%		Lenzen, 2008
	Convers.	**266**	**t_{UF6}/y**	
		180	***t_U/y***	
	Tailings	**(1.3)**	**t_{UF6}/y**	

Table 5: Mass balance calculations of Case 1

Phase	Parameter	Value	Unit	Source
(2) Enriching	Feed assay	0.711%	U-235	Lenzen, 2008
	Product assay	3.5%	U-235	Lenzen, 2008
	Tails assay	0.25%	U-235	Lenzen, 2008
	Enrich. method	30%	Diffusion	Lenzen, 2008
		70%	Centrifuge	Lenzen, 2008
	Enrich. effort	120 000	SWU/y	Hore-Lacy, 2004
	Enrich.	**38**	**t_{UF6}/y (enriched)**	
		25	***t_U/y***	
	Depleted uranium	**(227)**	**t_{UF6}/y (depleted)**	
		(153)	***t_U/y***	
	Fab. loss	1%		Lenzen, 2008
	Fuel fab.	**28**	**t_{UO2}/y**	
		25	***t_U/y***	
	Tailings	**(0.4)**	**t_{UF6}/y**	
		(0.3)	***t_U/y***	
Phase	Parameter	Value	Unit	Source
(3) Handling waste	Depleted uranium	227	t_{UF6}/y (depleted)	
	Spent used nuclear fuel	28	t_{USED}/y	
	Other waste from operation	13	t_{WASTE}/y	Lenzen, 2008
	Waste storage	**(256)**	**t_{HLW}/y**	
		(13)	**t_{LLW}/y**	
	Tailings	141 800	t_{ORE}/y	
		1	t_{U3O8}/y	
		1	t_{UF6}/y	
	Dismantling	10 000	t_{HLW}	Lenzen, 2008
		10 000	t_{ILW}	Lenzen, 2008
		100 000	t_{LLW}	Lenzen, 2008
	Lifetime	40	years	
	Waste disposal	**(300)**	**t_{HLW}/y**	
		(3 000)	**$t_{ILW/LLW}$/y**	
	Waste not sent to disposal	**13**	**t_{VLLW}/y**	
		(141 800)	**t_{ORE}/y**	

Table 5 (continued): Mass balance calculations of Case 1

4.2 Case 2: Nuclear energy (LWR power plant with reprocessing)

The protocol used for the mass balance evaluation of Case 2 is essentially the same as for Case 1. The only difference is that here the production process also includes the "Reprocessing" phase as shown in Figure 4 which uses the same symbols as described for Case 1.

It shall be noted that Figure 4 is only a representation of the general circulation of material flows and does not necessarily represent the reality of such flows at the level of one single power plant. Indeed, one LWR burns either natural enriched uranium or reprocessed fuel but not both at the same time as the figure would suggest. Therefore, Figure 4 should be understood as the general functioning of the overall nuclear energy system including relations between the various internal parts of this system (reactors, enrichment methods, reprocessing methods, etc.).

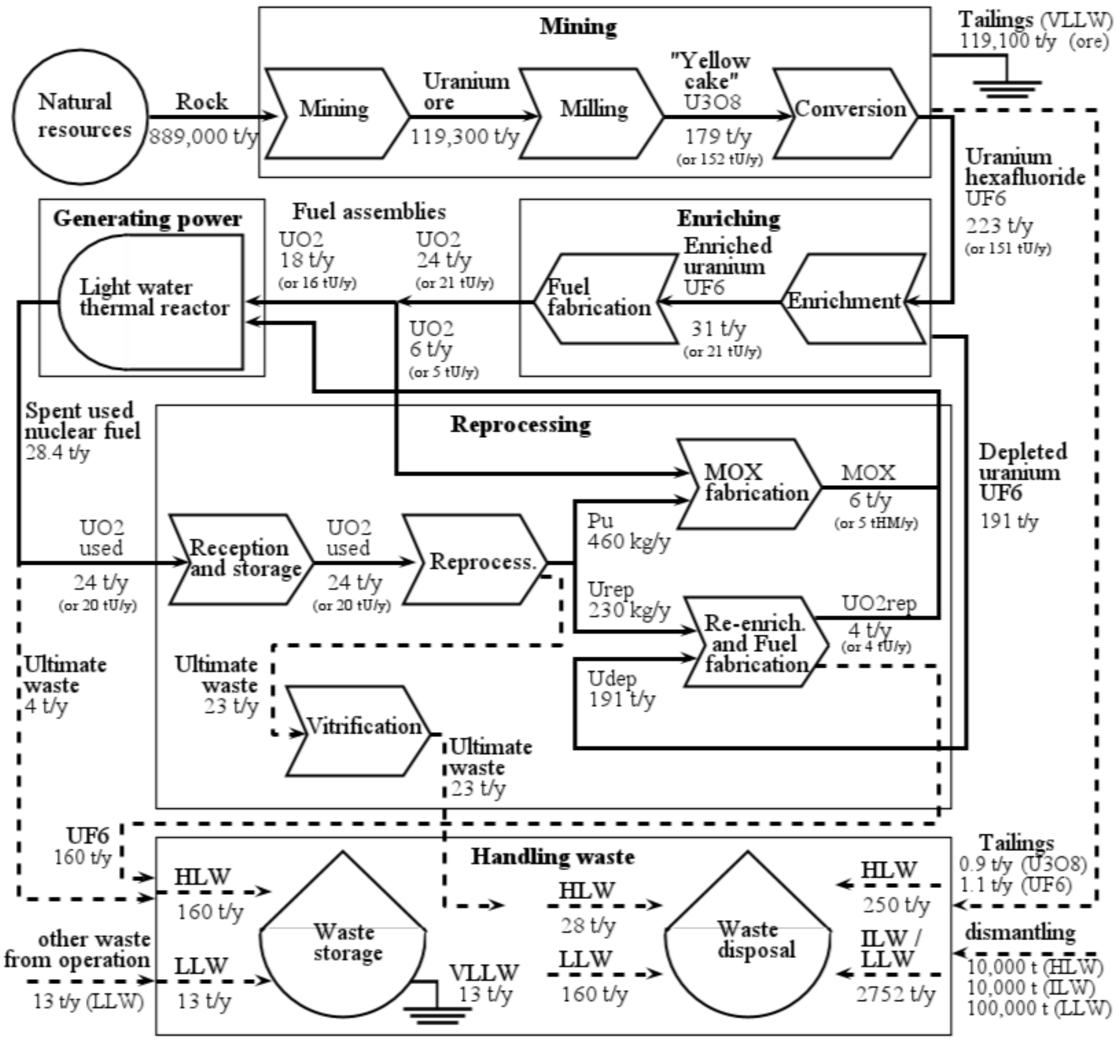

Figure 4: Mass balance of Case 2 (partly closed nuclear fuel cycle)

Table 6 presents the calculations of the material balance of Case 2. The specific aspects of this mass balance evaluation are detailed below:

- The presence of the reprocessing phase modifies the whole material balance of the system and especially the uranium enrichment process since less enriched uranium fuel is consumed in the system thanks to the recycling of part of the uranium and plutonium, the total heated material flow remaining the same between Cases 1 and 2 as explained in Section 3.2.2. In order to evaluate the mass balance for Case 2, several iterations have been necessary. Each iteration considers, first, the quantity of materials (uranium and plutonium) contained in both the used fuel (SNF) and the depleted uranium of Case 1. Second, the quantity of reprocessed fuels (MOX and UO2rep) that can be fabricated out of the recycled materials (Pu, Urep, and Udep) are evaluated. After iteration, it was found that the "Reprocessing" phase implies a reduction of 16% of the flow of enriched natural uranium needed in the system (entering into the LWR), and ultimately of the natural uranium needed to be extracted. This result is of the same order of magnitude as the MIT study which evaluates a reduction of the enriched uranium fuel demand up to 25% (Kazimi et al., 2011).
- The mass balance for the enrichment process has been evaluated starting from the reduced value of enriched uranium product equal to $32t_{UF6}/y$ (in contrast with the $38t_{UF6}/y$ of Case 1). Then, the three other variables (feed assay, tail assay and enrichment effort) are evaluated using the same calculator as for Case 1 (WISE, 2009a). Results of the mass balance evaluation for the enrichment process are shown in Table A.2 of the appendixes.
- The mass balance of the reprocessing phase has been directly evaluated using the calculator developed by the WISE Uranium Project (WISE, 2009b). The calculations of the mass balance for the reprocessing phase follow the same logic as for the enrichment process. As shown in Figure 5, all SNF materials (28t/y) are sent to the reprocessing plant which means that Case 2 represents the maximum reprocessing rate possible in a partly-closed nuclear fuel cycle. However, only 96% of the *fissile* materials can be recovered out of the SNF materials, meaning that almost all SNF materials are indeed sent to the storage and disposal facilities as ultimate waste, as shown in Figure 4.
- Results of the mass balance evaluation for each one of the three different processes (MOX fabrication, Urep and Udep re-enrichment) of the reprocessing phase are shown in Table A.3 of the appendixes.
    - Mixed oxide (MOX) fuel is a mixture of plutonium (with a given concentration of fissile plutonium, i.e. Pu-239 and Pu-241) and natural or depleted uranium. Here, I consider the MOX fuel as being a mix of plutonium and natural uranium (see Figure 4). Recycled uranium from depleted uranium (Udep) will rather be re-enriched in order to make reprocessed fuel (UO2rep) as explained below.
    - Udep is first re-enriched to natural assay, and then enriched further to fuel grade.
    - Urep is re-enriched to its initial enrichment equivalent, which is higher than the initial enrichment to compensate for the presence of impurities as explained earlier.

Phase	Parameter	Value	Unit	Source
(1) Mining	**Rock mined**	**889 000**	**t_{ROCK}/y**	
	Mining method	30%	open pit	Lenzen, 2008
		38%	ground excavation	Lenzen, 2008
		21%	in situ leaching	Lenzen, 2008
		11%	by-product of other mining	Lenzen, 2008
	Waste to ore ratio	9:1	Underground mining	US EPA, 2006
		3:1	Surface mining	US EPA, 2006
		7:1	(av.)	
	Recovery rate (yield)	94%		adapted from Lenzen, 2008
	Waste rock	**(770 000)**	**t_{ROCK}/y**	
	Ore recovered	**119 300**	**t_{ORE}/y**	
	Tailings	**(119 100)**	**t_{ORE}/y**	
	Ore grade	0.045%	U3O8 – Low (Australia)	Lenzen, 2008
		0.15%	U3O8 – baseline	Lenzen, 2008
		8%	U3O8 – High (Canada)	Lenzen, 2008
	Milling loss	0.5%		Lenzen, 2008
	Milling	**179**	**t_{U3O8}/y**	
		152	***t_U/y***	
	Tailings	**(0.9)**	**t_{U3O8}/y**	
	Conversion loss	0.5%		Lenzen, 2008
	Convers.	**223**	**t_{UF6}/y**	
		151	***t_U/y***	
	Tailings	**(1.1)**	**t_{UF6}/y**	

Table 6: Mass balance calculations of Case 2

Phase	Parameter	Value	Unit	Source
(2) Enriching	Feed assay	0.711%	U-235	Lenzen, 2008
	Product assay	3.5%	U-235	Lenzen, 2008
	Tails assay	0.25%	U-235	Lenzen, 2008
	Enrich. method	30%	Diffusion	Lenzen, 2008
		70%	Centrifuge	Lenzen, 2008
	Enrich. effort	**101 000**	SWU/y	
	Enrich.	**32**	**t_{UF6}/y (enriched)**	
		21	***t_U/y***	
	Depleted uranium	**(191)**	**t_{UF6}/y (depleted)**	
		(129)	***t_U/y***	
	Fab. loss	1%		Lenzen, 2008
	Fuel fab.	**24**	**t_{UO2}/y**	
		21	***t_U/y***	
	Tailings	**(0.3)**	**t_{UF6}/y**	
		(0.2)	***t_U/y***	

Table 6 (continued): Mass balance calculations of Case 2

Phase	Parameter	Value	Unit	Source
(3) Reprocess.	**SNF**	**28**	**t_{USED}/y**	
	Reprocess rate of SNF	100%	UO2 used	
	Compos. of SNF	95%	U-238	
		1%	U-235	
		2%	Pu	
		2%	fission prod. (waste)	
	Reception and storage	**24**	**t_{USED}/y**	
		20	***t_U/y***	
	SNF not reproc.	**(4)**	**t_{USED}/y**	
	Fissile material recovered	96%		
	Uranium recycled	**230**	**kg_{U-235}/y**	
	Plutonium recycled	**460**	**kg_{Pu}/y**	
	SNF not recovered	**(23)**	**t_{HLW}/y**	
	Uranium fuel consum.	6	t_{UO2}/y	
		5	*t_U/y*	
	Plutonium reproc. fuel fab.	**6**	**t_{MOX}/y**	
		5	***t_{HM}/y***	
	Uranium reproc. fuel fab.	**0.03**	**t_{UO2}/y**	
		0.03	***t_U/y***	
	Depleted uranium re-enrich.	**4**	**t_{UO2}/y**	
		4	***t_U/y***	

Table 6 (continued): Mass balance calculations of Case 2

Phase	Parameter	Value	Unit	Source
(4) Handling waste	Depleted uranium not recovered	160	t_{UF6}/y	
	SNF not reproc.	4	t_{USED}/y	
	Other waste from operation	13	t_{WASTE}/y	Lenzen, 2008
	Waste storage	**(160)**	**t_{HLW}/y**	
		13	**t_{LLW}/y**	
	Tailings	119 000	t_{ORE}/y	
		0.9	t_{U3O8}/y	
		1	t_{UF6}/y	
	Dismantling	10 000	t_{HLW}	Lenzen, 2008
		10 000	t_{ILW}	Lenzen, 2008
		100 000	t_{LLW}	Lenzen, 2008
	Lifetime	40	years	
	Waste disposal	**(270)**	**t_{HLW}/y**	
		(2 900)	**$t_{ILW/LLW}$/y**	
	Waste not sent to disposal	**(13)**	**t_{VLLW}/y**	
		(119 000)	**t_{ORE}/y**	

Table 6 (continued): Mass balance calculations of Case 2

4.3 Cases 3 and 4: Fossil energy

The material balance of the fossil energy system is not as complex as the one of the nuclear energy system. This is due to a whole process being more simple with less unit operations, even when adding a CCS technology to the system, as shown in the example of Figure 5. The relative simplicity of the whole process with fossil energy already appears as an indicator of a better performance since reducing the number of steps helps reducing the biophysical requirements for the making and maintenance of the flows and funds of the system.

Tables 7 and 8 present the calculations of the material balance for Case 3 and 4 respectively. These tables consider the following assumptions:

- The material balance of the fossil energy production process is only performed for the “Mining” phase. Indeed, losses during the “Refining” phase are considered negligible, so that the flow of coal is considered being the same for the two mining and refining processes.
- As explained in Section 3.2.3, the average heating value of coal (26 GJ/t) is evaluated based on the individual heating values of each type of coal resources from the 2007 MIT study on coal (Katzer et al., 2007) and distributed according to the share of each resource type in the coal mining market (U.S. EIA, 2010). As far as the share between underground mining (60%) and surface mining (40%) (WCI, 2009), those values will be used for the evaluation of the biophysical requirements of the fossil energy system.

- In Table 8, the carbon-capture efficiency of the CCS technology is considered equal to 90% (Katzer et al., 2007; US DOE/NETL, 2011a) so that only 10% of the total direct CO2 emissions from the power plant remain released into the atmosphere after capture. Moreover, it is shown in the figure that the total amount of CO2 emitted by the power plant is not the same between Case 1 ($2.9Mt_{CO2}/y$) and Case 2 ($3.2Mt_{CO2}/y$). This is due to the CCS system of Case 2 which requires of a higher demand of coal in order to compensate the reduction in the Rankine cycle efficiency (see Section 3.2.4).

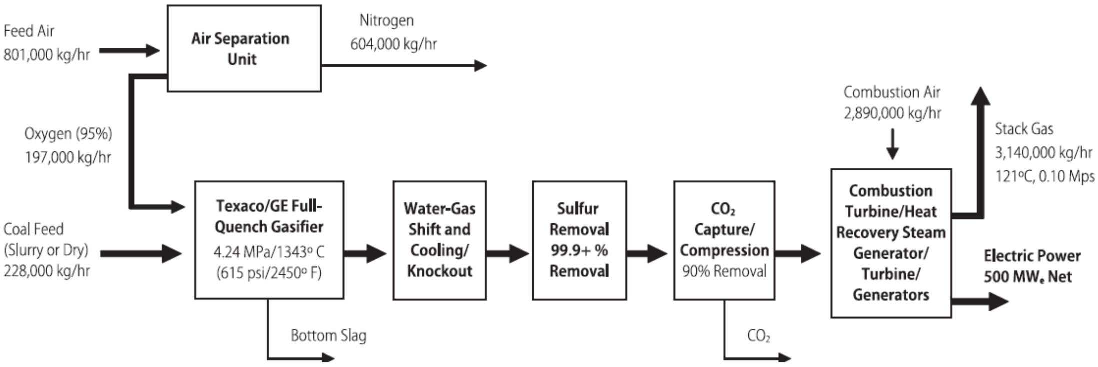

Figure 5: Example of a 500 MWe IGCC unit with CCS (source: Katzer et al., 2007)

Phase	Parameter	Value	Unit	Source
(1) Mining and Refining	Recov. reserves	50%	Bituminous and anthracite	after US EIA, 2010
		32%	Sub-bit.	after US EIA, 2010
		18%	Lignite	after US EIA, 2010
	Heating value	30	GJ/t_{coal} (Bit. and anth.)	Katzer et al., 2007
		25	GJ/t_{coal} (Subbit.)	Katzer et al., 2007
		15	GJ/t_{coal} (Lignite)	Katzer et al., 2007
		26	GJ/t_{coal} (av.)	
	Mining method	40%	Surface mining	WCI, 2009
		60%	Underground mining	WCI, 2009
(3) Handling waste	CO2 captured	0	Mt_{CO2}/y	after Katzer et al., 2007
	CO2 emitted	2.9	Mt_{CO2}/y	after Katzer et al., 2007

Table 7: Mass balance calculations of Case 3

Phase	Parameter	Value	Unit	Source
(1) Mining and Refining	Recov. reserves	50%	Bituminous and anthracite	after US EIA, 2010
		32%	Sub-bit.	after US EIA, 2010
		18%	Lignite	after US EIA, 2010
	Heating value	30	GJ/t_{coal} (Bit. and anth.)	Katzer et al., 2007
		25	GJ/t_{coal} (Subbit.)	Katzer et al., 2007
		15	GJ/t_{coal} (Lignite)	Katzer et al., 2007
		26	GJ/t_{coal} (av.)	
	Mining method	40%	Surface mining	WCI, 2009
		60%	Underground mining	WCI, 2009
(3) Handling waste	CO2 captured at 90% efficiency	3.2	$Mt_{captured}/y$	after Katzer et al., 2007
	CO2 emitted	0.4	$Mt_{emitted}/y$	after Katzer et al., 2007

Table 8: Mass balance calculations of Case 4

5. Evaluation of the biophysical requirements

This section presents the following biophysical requirements for the four baseline cases presented in Section 3 and whose internal consumption of flows have been characterized in Section 4: (i) electricity; (ii) fossil-fuels, (iii) labor; and (iv) materials. Each type of biophysical requirement is allocated whether it expresses the function of "what the system does" (direct consumption in relation to the flows) or "what the system is" (indirect consumption in relation to the making and maintenance of the funds).

I focus here on the four types of biophysical requirements identified above for the phases that both nuclear energy and fossil energy have in common: (i) mining; (ii) refining/enriching; (iii) generating power; and (iv) handling pollution/radioactive waste (see Figure 2).

5.1 Electricity requirements

5.1.1 Nuclear energy

The electricity requirements—as well as the fossil-fuel requirements presented in Section 5.2—for nuclear energy have been evaluated using Lenzen's (2008) meta-analysis of about 100 life-cycle assessments (LCA). The data provided only concern the electricity requirements in relation to the flows—i.e. electricity requirements for the making and maintenance of the funds are not provided in the report. Nevertheless, those indirect requirements can be considered as negligible in comparison to direct consumption of electricity by the system.

Tables 9 and 10 present, respectively, the direct electricity requirements (flows) and the corresponding specific electricity requirements expressed in relation to the *gross* electricity output for Case 1.

Phase	Process	min	MAX	mean	Error	Unit	Source
(1) Mining	Mining			not included			Lenzen, 2008
	Milling			not included			Lenzen, 2008
	Convers.	15	21	18	± 3.2	MWh_{el}/t_U	Lenzen, 2008
(2) Enriching	Enrich.	-	-	790	-	kWh_{el}/SWU	after Lenzen, 2008
	Fuel fab.	48	301	145	± 106.0	MWh_{el}/t_U	Lenzen, 2008
(3) Generating power	Operation	-	-	8.5	-	GWh_{el}/y	Lenzen, 2008
(4) Handling waste	Waste storage	-	-	80	-	MWh_{el}/t_{HLW}	Lenzen, 2008
				not included		$MWh_{el}/t_{ILW/LLW}$	Lenzen, 2008
	Waste disposal	-	-	329	-	MWh_{el}/t_{HLW}	Lenzen, 2008
		-	-	24	-	$MWh_{el}/t_{ILW/LLW}$	Lenzen, 2008

Table 9: Direct electricity requirements (flows) – Case 1

Phase	Process	min	MAX	mean	Error	Unit
(1) Mining	Mining			not included		
	Milling			not included		
	Convers.	0.29	0.42	0.36	± 0.06	MWh_{el}/GWh_{el}^*
(2) Enriching	Enrich.	-	-	11	-	MWh_{el}/GWh_{el}^*
	Fuel fab.	0.13	0.84	0.40	± 0.30	MWh_{el}/GWh_{el}^*
(3) Generating power	Operation	-	-	0.94	-	MWh_{el}/GWh_{el}^*
(4) Handling waste	Waste storage	-	-	2.3	-	MWh_{el}/GWh_{el}^*
	Waste disposal	-	-	19	-	MWh_{el}/GWh_{el}^*
TOTAL		**-**	**-**	**33**	**± 0.4**	$\mathbf{MWh_{el}/GWh_{el}^*}$

Table 10: Specific direct electricity requirements (flows) – Case 1
*: Values expressed in relation to the *gross* electricity output.

Then, in Table 11, we can evaluate the net electricity generated by the system (Case 1) which can directly be derived from Table 10 showing the internal electricity requirement of the overall system.

Electricity output	9000 GWh_{el}/y	*Table 1*
Electricity input	300 GWh_{el}/y	*after Table 10*
Net electricity generated	**8700** $\mathbf{GWh_{el}/y}$	

Table 11: Net electricity generated – Case 1

Following the same logic as for Case 1, Tables 12–14 present the direct electricity requirements, the specific electricity requirements and the net electricity generated for Case 2.

Since no data have been found for the electricity requirements—as well as for the fossil-fuel requirements—of the "Reprocessing" phase—which is still at an experimental stage as explained in Section 3.1—the following assumptions have been made in the following tables:

- The reception and storage process is considered having the same requirements as the waste storage process of the "Handling waste" phase.
- The reprocessing and the vitrification processes are considered having the same requirements as the operation process of the "Generating power" phase.
- The MOX and UO2 fuel fabrication processes are considered having the same requirements as the fuel fabrication process of the "Enriching" phase.
- The Urep and Udep re-enrichment process has the same requirements as the enrichment process of the "Enriching" phase (same facilities).

Phase	Process	min	MAX	mean	Error	Unit	Source
(1) Mining	Mining			not included			Lenzen, 2008
	Milling			not included			Lenzen, 2008
	Convers.	15	21	18	± 3.2	MWh_{el}/t_U	Lenzen, 2008
(2) Enriching	Enrich.	-	-	790.0	-	kWh_{el}/SWU	after Lenzen, 2008
	Fuel fab.	48	301	145	± 106	MWh_{el}/t_U	Lenzen, 2008
(3) Generating power and Reprocess.	Operation	-	-	8.5	-	GWh_{el}/y	Lenzen, 2008
	Reception and storage	-	-	80	-	MWh_{el}/t_{HLW}	
	Reprocess.	-	-	8.5	-	GWh_{el}/y	
	MOX fuel fab.	48	301	145	± 106	MWh_{el}/t_{HM}	
	Urep and Udep re-enrich.	-	-	790.0	-	kWh_{el}/SWU	
	UO2-rep fuel fab.	48	301	145	± 106	MWh_{el}/t_U	
	Vitrification	-	-	8.5	-	GWh_{el}/y	
(4) Handling waste	Waste storage	-	-	80	-	MWh_{el}/t_{HLW}	Lenzen, 2008
				not included		$MWh_{el}/t_{ILW/LLW}$	Lenzen, 2008
	Waste disposal	-	-	329	-	MWh_{el}/t_{HLW}	Lenzen, 2008
		-	-	24	-	$MWh_{el}/t_{ILW/LLW}$	Lenzen, 2008

Table 12: Direct electricity requirements (flows) – Case 2

Phase	Process	min	MAX	mean	Error	Unit
(1) Mining	Mining			not included		
	Milling			not included		
	Convers.	0.24	0.35	0.30	± 0.054	MWh_{el}/GWh_{el}^{*}
(2) Enriching	Enrich.	-	-	8.9	-	MWh_{el}/GWh_{el}^{*}
	Fuel fab.	0.11	0.71	0.34	± 0.25	MWh_{el}/GWh_{el}^{*}
(3) Generating power and Reprocess.	Operation	-	-	0.94	-	MWh_{el}/GWh_{el}^{*}
	Reception and storage	-	-	1.4	-	MWh_{el}/GWh_{el}^{*}
	Reprocess.	-	-	0.94	-	MWh_{el}/GWh_{el}^{*}
	Fuel fab. and Vitrification	-	-	2.6	± 0.10	MWh_{el}/GWh_{el}^{*}
(4) Handling waste	Waste storage	-	-	1.4	-	MWh_{el}/GWh_{el}^{*}
	Waste disposal	-	-	18	-	MWh_{el}/GWh_{el}^{*}
TOTAL		**-**	**-**	**34**	**± 0.4**	$\mathbf{MWh_{el}/GWh_{el}^{*}}$

Table 13: Specific direct electricity requirements (flows) – Case 2
*: Values expressed in relation to the *gross* electricity output.

Electricity output	9000 GWh_{el}/y	*Table 2*
Electricity input	300 GWh_{el}/y	*after Table 13*
Net electricity generated	**8700** $\mathbf{GWh_{el}/y}$	

Table 14: Net electricity generated – Case 2

5.1.2 Fossil energy

The electricity requirements—as well as the fossil-fuel requirements—for fossil energy have been evaluated using the U.S. Department of Energy study (US DOE/NETL, 2010b) that performs an LCA for three recent IGCC designs. For Case 4, the electricity requirements of the CCS technology have been evaluated using an LCA of a pulverized coal power plant which provides details for the capture, compression, transportation and injection processes (Koornneef et al., 2008).

5.1.2.1 Direct electricity requirements and net electricity generated

Tables 15–17 present the direct electricity requirements, the specific electricity requirements and the net electricity generated for Case 3.

Phase	Process	Value	Unit	Source
(1) Mining and Refining	Mining and Cleaning	33	MJ_{el}/t_{coal}	US DOE/NETL, 2010b
	Transport.	not included		
(2) Generating power	Operation	not included		
(3) Handling waste		N/A		

Table 15: Direct electricity requirements (flows) – Case 3

Phase	Process	Value	Unit
(1) Mining and Refining	Mining and Cleaning	3.2	$MWh_{el}/GWh_{el}{}^{*}$
	Transport.	not included	
(2) Generating power	Operation	not included	
(3) Handling waste		N/A	
TOTAL		**3.2**	$\mathbf{MWh_{el}/GWh_{el}{}^{*}}$

Table 16: Specific direct electricity requirements (flows) – Case 3
*: Values expressed in relation to the *gross* electricity output.

Electricity output	4200	GWh_{el}/y	*Table 3*
Electricity input	10	GWh_{el}/y	*after Table 16*
Net electricity generated	**4190**	$\mathbf{GWh_{el}/y}$	

Table 17: Net electricity generated – Case 3

Following the same logic as for Case 3, Tables 18–20 present the direct electricity requirements, the specific electricity requirements and the net electricity generated for Case 4.

Phase	Process	min	MAX	mean	Error	Unit	Source
(1) Mining and Refining	Mining and Cleaning	-	-	33	-	MJ_{el}/t_{coal}	US DOE/NETL, 2010b
	Transport.			not included			
(2) Generating power	Operation			not included			
(3) Handling waste	Capture	16.6	30.5	23.6	± 6.9	$kWh_{el}/t_{captured}$	Koornneef et al., 2008
	Compress. and Transport	-	-	111	-	$kWh_{el}/t_{captured}$	Koornneef et al., 2008
	Injection	-	-	7	-	$kWh_{el}/t_{captured}$	Koornneef et al., 2008

Table 18: Direct electricity requirements (flows) – Case 4

Phase	Process	min	MAX	mean	Error	Unit
(1) Mining and Refining	Mining and Cleaning	-	-	3.8	-	MWh_{el}/GWh_{el}*
	Transport.			not included		
(2) Generating power	Operation			not included		
(3) Handling waste	Capture, Compress., Transport and Storage	-	-	120	± 6	MWh_{el}/GWh_{el}*
TOTAL		**-**	**-**	**120**	**± 6**	**MWh_{el}/GWh_{el}***

Table 19: Specific direct electricity requirements (flows) – Case 4
*: Values expressed in relation to the *gross* electricity output.

Electricity output	3700 GWh_{el}/y	*Table 4*
Electricity input	460 GWh_{el}/y	*after Table 19*
Net electricity generated	**3240 GWh_{el}/y**	

Table 20: Net electricity generated – Case 4

5.1.2.2 Indirect electricity requirements

Tables 21 and 22 present the indirect electricity requirements and the corresponding specific electricity requirements—considering a plant lifetime of 30 years (US DOE/NETL, 2011a)—for Case 3.

Phase	Process	Value	Unit	Source
(1) Mine and Refinery	Construct. and Dismantling	not included		
(2) Power plant	Construct.	1.144	MJ_{el}/MWh_{el}	US DOE/NETL, 2010b
	Maint.	not included		
	Dismantling	not included		
(3) Waste facility		N/A		

Table 21: Indirect electricity requirements (funds) – Case 3

Phase	Process	Value	Unit
(1) Mine and Refinery	Construct. and Dismantling	not included	
(2) Power plant	Construct., Maint. and Dismantling	0.32	MWh_{el}/GWh_{el}
(3) Waste facility		N/A	
TOTAL		**0.32**	**MWh_{el}/GWh_{el}**

Table 22: Specific indirect electricity requirements (funds) – Case 3

Following the same logic as for Case 3, Tables 23 and 24 present the indirect electricity requirements and the corresponding specific electricity requirements for Case 4.

Phase	Process	Value	Unit	Source
(1) Mine and Refinery	Construct. and Dismantling	not included		
(2) Power plant (incl. Capture and Compress.)	Construct.	1.166	MJ_{el}/MWh_{el}	US DOE/NETL, 2010b
	Maint.	not included		
	Dismantling	not included		
(3) Waste facility (Transport infra.)	Construct., Maint. and Dismantling	not included		

Table 23: Indirect electricity requirements (funds) – Case 4

Phase	Process	Value	Unit
(1) Mine and Refinery	Construct. and Dismantling	not included	
(2) Power plant (incl. Capture and Compress.)	Construct., Maint. and Dismantling	0.32	MWh_{el}/GWh_{el}
(3) Waste facility (Transport infra.)	Construct., Maint. and Dismantling	not included	
TOTAL		**0.32**	**MWh_{el}/GWh_{el}**

Table 24: Specific indirect electricity requirements (funds) – Case 4

5.2 Fossil-fuel requirements

5.2.1 Nuclear energy

The fossil-fuel requirements for nuclear energy consider the same reference and assumptions as for the electricity requirements presented in Section 5.1.

5.2.1.1 Direct fossil-fuel requirements

Tables 25 and 26 present, respectively, the direct fossil-fuel requirements (flows) and the corresponding specific fossil-fuel requirements expressed in relation to the *net* electricity output for Case 1.

Phase	Process	min	MAX	mean	Error	Unit	Source
(1) Mining	Mining	-	-	339	-	GJ/t_U	after Lenzen, 2008
	Milling	-	-	717	-	GJ/t_U	after Lenzen, 2008
	Convers.	155	396	276	± 120.5	MWh_{th}/t_U	Lenzen, 2008
(2) Enriching	Enrich.	-	-	19.7	-	kWh_{th}/SWU	after Lenzen, 2008
	Fuel fab.	3	6170	1403	± 1966	GJ/t_U	Lenzen, 2008
(3) Generating power	Operation	38	889	255	± 227.0	$GWh_{th}/GW_{el}/y$	Lenzen, 2008
(4) Handling waste	Waste storage	-	-	600	-	MWh_{th}/t_{HLW}	Lenzen, 2008
		-	-	400	-	$MWh_{th}/t_{ILW/LLW}$	Lenzen, 2008
	Waste disposal			not included		MWh_{th}/t_{HLW}	Lenzen, 2008
				not included		$MWh_{th}/t_{ILW/LLW}$	Lenzen, 2008

Table 25: Direct fossil-fuel requirements (flows) – Case 1

Phase	Process	min	MAX	mean	Error	Unit
(1) Mining	Mining	-	-	8.3	-	GJ/GWh_{el}
	Milling	-	-	15	-	GJ/GWh_{el}
	Convers.	12	29	20	± 9.0	GJ/GWh_{el}
(2) Enriching	Enrich.	-	-	1.0	-	GJ/GWh_{el}
	Fuel fab.	0.0087	18	4.1	± 5.7	GJ/GWh_{el}
(3) Generating power	Operation	20	480	140	± 120	GJ/GWh_{el}
(4) Handling waste	Waste storage	-	-	66	-	GJ/GWh_{el}
	Waste disposal			not included		
TOTAL		**-**	**-**	**250**	**± 130**	$\mathbf{GJ/GWh_{el}}$

Table 26: Specific direct fossil-fuel requirements (flows) – Case 1

Following the same logic as for Case 1, Tables 27 and 28 present the direct fossil-fuel requirements and the corresponding specific fossil-fuel requirements for Case 2.

Phase	Process	min	MAX	mean	Error	Unit	Source
(1) Mining	Mining	-	-	339	-	GJ/t_U	after Lenzen, 2008
	Milling	-	-	717	-	GJ/t_U	after Lenzen, 2008
	Convers.	155	396	276	± 121	MWh_{th}/t_U	Lenzen, 2008
(2) Enriching	Enrich.	-	-	19.7	-	kWh_{th}/SWU	after Lenzen, 2008
	Fuel fab.	3	6170	1403	± 1966	GJ/t_U	Lenzen, 2008
(3) Generating power and Reprocess.	Operation	38	889	255	± 227	$GWh_{th}/GW_{el}/y$	Lenzen, 2008
	Reception and storage	-	-	600	-	MWh_{th}/t_{USED}	
	Reprocess.	-	-	255	-	$GWh_{th}/GW_{el}/y$	
	MOX fuel fab.	3	6170	1403	± 1966	GJ/t_{HM}	
	Urep and Udep re-enrich.	-	-	19.7	-	kWh_{th}/SWU	
	UO2-rep fuel fab.	3	6170	1403	± 1966	GJ/t_U	
	Vitrification	-	-	255	-	$GWh_{th}/GW_{el}/y$	
(4) Handling waste	Waste storage	-	-	600	-	MWh_{th}/t_{HLW}	Lenzen, 2008
		-	-	400	-	$MWh_{th}/t_{ILW/LLW}$	Lenzen, 2008
	Waste disposal			not included		MWh_{th}/t_{HLW}	Lenzen, 2008
				not included		$MWh_{th}/t_{ILW/LLW}$	Lenzen, 2008

Table 27: Direct fossil-fuel requirements (flows) – Case 2

Phase	Process	min	MAX	mean	Error	Unit
(1) Mining	Mining	-	-	7.0	-	GJ/GWh_{el}
	Milling	-	-	13	-	GJ/GWh_{el}
	Convers.	10	25	17	± 7.5	GJ/GWh_{el}
(2) Enriching	Enrich.	-	-	0.8	-	GJ/GWh_{el}
	Fuel fab.	0.007	15	3.4	± 4.8	GJ/GWh_{el}
(3) Generating power and Reprocess.	Operation	20	480	140	± 120	GJ/GWh_{el}
	Reception and storage	-	-	5.9	-	GJ/GWh_{el}
	Reprocess.	-	-	140	-	GJ/GWh_{el}
	Fuel fab. and Vitrification	-	-	110	± 2.0	GJ/GWh_{el}
(4) Handling waste	Waste storage	-	-	42	-	GJ/GWh_{el}
	Waste disposal			not included		
TOTAL		**-**	**-**	**480**	**± 130**	**GJ/GWh_{el}**

Table 28: Specific direct fossil-fuel requirements (flows) – Case 2

5.2.1.2 Indirect fossil-fuel requirements

Tables 29 and 30 present, respectively, the indirect fossil-fuel requirements (funds) and the corresponding specific fossil-fuel requirements expressed in relation to the *net* electricity output—considering a plant lifetime of 40 years (Table 6)—for Case 1.

Phase	Process	min	MAX	mean	Error	Unit	Source
(1) Mine	Mining	-	-	505	-	GJ/t_U	after Lenzen, 2008
	Milling	-	-	435	-	GJ/t_U	after Lenzen, 2008
	Convers.			not included			Lenzen, 2008
(2) Enrich. plant	Enrich. Plant	-	-	215.4	-	kWh_{th}/SWU	after Lenzen, 2008
	Fab. Plant			not included			Lenzen, 2008
(3) Power plant	Construct.	2806	3613	3209.6	± 403.4	GWh_{th}/GW_{el}	after Lenzen, 2008
	Maint.			not included			Lenzen, 2008
	Dismantling	4.3	6.2	5.2	± 1.0	PJ	after Lenzen, 2008
(4) Waste facilities	Waste storage			not included			Lenzen, 2008
	Waste disposal	-	-	119	-	MWh_{th}/t_{HLW}	Lenzen, 2008
		-	-	1	-	$MWh_{th}/t_{ILW/LLW}$	Lenzen, 2008

Table 29: Indirect fossil-fuel requirements (funds) – Case 1

Phase	Process	min	MAX	mean	Error	Unit
(1) Mine	Mining	-	-	12	-	GJ/GWh_{el}
	Milling	-	-	9.0	-	GJ/GWh_{el}
	Convers.			not included		
(2) Enrich. plant	Enrich. Plant	-	-	11	-	GJ/GWh_{el}
	Fab. Plant			not included		
(3) Power plant	Construct.	13 000	17 000	15 000	± 2 000	TJ
	Maint.			not included		
	Dismantling	4 300	6 200	5 200	± 1 000	TJ
(4) Waste facilities	Waste storage			not included		
	Waste disposal	-	-	16	-	GJ/GWh_{el}
TOTAL		**-**	**-**	**110**	**± 9**	**GJ/GWh_{el}**

Table 30: Specific indirect fossil-fuel requirements (funds) – Case 1

Following the same logic as for Case 1, Tables 31 and 32 present the indirect fossil-fuel requirements and the corresponding specific fossil-fuel requirements for Case 2.

For the same reason of absence of data for the fossil-fuel requirements of the "Reprocessing" phase explained in Section 5.1, the following assumption has been made for the indirect consumption of fossil-fuels:

- The requirements for the construction, maintenance and dismantling processes of the "Reprocessing plant" phase are considered being the same as for the "Enrichment plant" phase (same facilities).

Phase	Process	min	MAX	mean	Error	Unit	Source
(1) Mine	Mining	-	-	505	-	GJ/t_U	after Lenzen, 2008
	Milling	-	-	435	-	GJ/t_U	after Lenzen, 2008
	Convers.			not included			Lenzen, 2008
(2) Enrich. plant	Enrich. Plant	-	-	215	-	kWh_{th}/SWU	after Lenzen, 2008
	Fab. Plant			not included			Lenzen, 2008
(3) Power plant and Reprocess. plant	Construct.	2806	3613	3210	± 403	GWh_{th}/GW_{el}	after Lenzen, 2008
	Maint.			not included			Lenzen, 2008
	Dismantling	4.3	6.2	5.2	± 1.0	PJ	after Lenzen, 2008
	Reprocess. Plant	-	-	215	-	kWh_{th}/SWU	
(4) Waste facilities	Waste storage			not included			Lenzen, 2008
	Waste disposal	-	-	119	-	MWh_{th}/t_{HLW}	Lenzen, 2008
		-	-	1	-	$MWh_{th}/t_{ILW/LLW}$	Lenzen, 2008

Table 31: Indirect fossil-fuel requirements (funds) – Case 2

Phase	Process	min	MAX	mean	Error	Unit
(1) Mine	Mining	-	-	10	-	GJ/GWh_{el}
	Milling	-	-	7.6	-	GJ/GWh_{el}
	Convers.			not included		
(2) Enrich. plant	Enrich. Plant	-	-	9.0	-	GJ/GWh_{el}
	Fab. Plant			not included		
(3) Power plant and Reprocess. plant	Construct.	13,000	17,000	15,000	± 2,000	TJ
	Maint.			not included		
	Dismantling	4,300	6,200	5,200	± 1,000	TJ
	Reprocess. Plant	-	-	1.5	-	GJ/GWh_{el}
(4) Waste facilities	Waste storage			not included		
	Waste disposal	-	-	14	-	GJ/GWh_{el}
TOTAL		**-**	**-**	**100**	**± 9**	**GJ/GWh_{el}**

Table 32: Specific indirect fossil-fuel requirements (funds) – Case 2

5.2.2 Fossil energy

The fossil-fuel requirements for fossil energy consider the same reference as for the electricity requirements presented in Section 5.1.

It shall be noted that the consumption of coal in the fossil-energy system must not be included in this section since it corresponds to the consumption in terms of primary energy sources—like uranium for the nuclear energy system—while the fossil-fuel requirements reflect the consumption in terms of energy carriers (mostly diesel, US DOE/NETL, 2011b).

5.2.2.1 Direct fossil-fuel requirements

Tables 33 and 34 present, respectively, the direct fossil-fuel requirements (flows) and the corresponding specific fossil-fuel requirements expressed in relation to the *net* electricity output for Case 3.

Phase	Process	Value	Unit	Source
(1) Mining and Refining	Mining and Cleaning	2.62E-04	toe/t_{coal}	US DOE/NETL, 2010b
	Transport.	9.79E-03	toe/t_{coal}	US DOE/NETL, 2010b
(2) Generating power	Operation	0.16	toe/GWh_{el}	US DOE/NETL, 2010b
(3) Handling waste		N/A		
	Net calorific value	43.38	GJ/toe	OECD/IEA, 2005

Table 33: Direct fossil-fuel requirements (flows) – Case 3

Phase	Process	Value	Unit
(1) Mining and Refining	Mining and Cleaning	3.9	GJ/GWh_{el}
	Transport.	147	GJ/GWh_{el}
(2) Generating power	Operation	7.0	GJ/GWh_{el}
(3) Handling waste		N/A	
TOTAL		**160**	**GJ/GWh_{el}**

Table 34: Specific direct fossil-fuel requirements (flows) – Case 3

Following the same logic as for Case 3, Tables 35 and 36 present the direct fossil-fuel requirements and the corresponding specific fossil-fuel requirements for Case 4.

Phase	Process	Value	Unit	Source
(1) Mining and Refining	Mining and Cleaning	2.62E-04	toe/t_{coal}	US DOE/NETL, 2010b
	Transport.	9.79E-03	toe/t_{coal}	US DOE/NETL, 2010b
(2) Generating power	Operation	0.19	toe/GWh_{el}	US DOE/NETL, 2010b
(3) Handling waste	Capture, Compress., Transport and Storage	not included		
	Net calorific value	43.38	GJ/toe	OECD/IEA, 2005

Table 35: Direct fossil-fuel requirements (flows) – Case 4

Phase	Process	Value	Unit
(1) Mining and Refining	Mining and Cleaning	5.4	GJ/GWh$_{el}$
	Transport.	200	GJ/GWh$_{el}$
(2) Generating power	Operation	8.1	GJ/GWh$_{el}$
(3) Handling waste	Capture, Compress., Transport and Storage	not included	
TOTAL		**210**	**GJ/GWh$_{el}$**

Table 36: Specific direct fossil-fuel requirements (flows) – Case 4

5.2.2.2 Indirect fossil-fuel requirements

Tables 37 and 38 present, respectively, the indirect fossil-fuel requirements (funds) and the corresponding specific fossil-fuel requirements expressed in relation to the *net* electricity output—considering the same plant lifetime of 30 years as discussed in Section 5.1—for Case 3.

Phase	Process	Value	Unit	Source
(1) Mine and Refinery	Construct.	2.0E-04	MJ$_{th}$/t$_{coal}$	US DOE/NETL, 2010b
	Dismantling	2.42E-06	toe/t$_{coal}$	US DOE/NETL, 2010b
(2) Power plant	Construct.	0.0017	MJ$_{th}$/MWh$_{el}$	US DOE/NETL, 2010b
	Maint.	not included		
	Dismantling	0.052	toe/GWh$_{el}$	US DOE/NETL, 2010b
(3) Waste facility		N/A		

Table 37: Indirect fossil-fuel requirements (funds) – Case 3

Phase	Process	Value	Unit
(1) Mine and Refinery	Construct.	6.8E-05	GJ/GWh$_{el}$
	Dismantling	3.6E-02	GJ/GWh$_{el}$
(2) Power plant	Construct.	1.7E-03	GJ/GWh$_{el}$
	Maint.	not included	
	Dismantling	2.2	GJ/GWh$_{el}$
(3) Waste facility		N/A	
TOTAL		**2.3**	**GJ/GWh$_{el}$**

Table 38: Specific indirect fossil-fuel requirements (funds) – Case 3

Following the same logic as for Case 3, Tables 39 and 40 present the indirect fossil-fuel requirements and the corresponding specific fossil-fuel requirements for Case 4.

Phase	Process	Value	Unit	Source
(1) Mine and Refinery	Construct.	2.0E-04	MJ_{th}/t_{coal}	US DOE/NETL, 2010b
	Dismantling	2.42E-06	toe/t_{coal}	US DOE/NETL, 2010b
(2) Power plant (incl. Capture and Compress.)	Construct.	0.0019	MJ_{th}/MWh_{el}	US DOE/NETL, 2010b
	Maint.	not included		
	Dismantling	0.052	toe/GWh_{el}	US DOE/NETL, 2010b
(3) Waste facility (Transport infra.)	Construct., Maint. and Dismantling	165,500	GJ	Koornneef et al., 2008

Table 39: Indirect fossil-fuel requirements (funds) – Case 4

Phase	Process	Value	Unit
(1) Mine and Refinery	Construct.	9.2E-05	GJ/GWh_{el}
	Dismantling	4.9E-02	GJ/GWh_{el}
(2) Power plant	Construct.	1.9E-03	GJ/GWh_{el}
	Maint.	not included	
	Dismantling	2.2	GJ/GWh_{el}
(3) Waste facility (Transport infra.)	Construct., Maint. and Dismantling	1.7	GJ/GWh_{el}
TOTAL		**4.0**	$\mathbf{GJ/GWh_{el}}$

Table 40: Specific indirect fossil-fuel requirements (funds) – Case 4

5.3 Labor requirements

5.3.1 Nuclear energy

Labor requirements are difficult to evaluate in the case of nuclear energy given the qualitative and quantitative differentiation of its production process which makes it difficult to identify the real needs for a given baseline case and at a given time. This problem has been acknowledged by the IAEA saying that "data are scarce on the number of people today with the various skills needed in the nuclear industry" (OECD/IAEA, 2010). In order to overcome this problem, I consider the following approach for each phase of the nuclear energy system (Cases 1 and 2):

- Labor productivity of the "Mining" phase has been evaluated considering the different countries for which both annual employment, production and average grade were provided (OECD/IAEA, 2004). Based on Table A.4 of the appendices presenting details of the labor requirement evaluation, an average productivity of $80t_{ORE}$/man-year has been obtained. Note that the uranium mining productivity cannot directly be compared with the coal mining productivity because the amount of uranium ore needed to be mined is much higher than the nuclear fuel that will be fabricated out of the ore (see Figure 3).
- Labor requirements for the "Enriching" phase have been derived from Rothwell's studies on uranium enrichment (Rothwell, 2009) and nuclear fuel fabrication (Rothwell, 2010) which provide results per unit of materials.

- Labor requirements for the "Generating power" phase (operation, construction, maintenance and dismantling processes) have been found in NEI, 2010. On that respect, R&D efforts for the nuclear power plant design are significant so that they have been considered in Tables 41 and 42 presenting the data labor requirements.
- Labor requirements for the dismantling of the power plant are also difficult to evaluate. Indeed, the experience of the first dismantlements around the world has shown high variations in terms of financial costs (Lenzen, 2008) even exceeding in some cases the costs of construction of the facility, and so it is the case for labor requirements. I consider here an average dismantling cost of 35% of the construction cost (Lenzen, 2008).
- Labor requirements for the "Handling waste" phase are evaluated considering the case of France where employment at the ANDRA—the French agency in charge of waste management—makes it possible to isolate labor requirements distributed in terms of waste categories (HLW, ILW and LLW).
- For Case 4, labor requirements for the "Reprocessing" phase are based on the French experience of the La Hague site. Although, this site includes both a waste disposal and a waste reprocessing plant, I consider here that the HLW waste being reprocessed at La Hague would have to be managed anyway—be it postponed in the future. As a result, labor requirements allocated to the "Reprocessing" phase in the report implicitly include the ones for handling HLW waste—although not ILW and LLW of much higher amounts (see Figures 3 and 4).
- In order to express the labor requirements in terms of hours, 1,800 annual working hours have been considered for both nuclear energy and fossil energy systems which correspond to the average value in the OECD countries (OECD, 2008).

Tables 41 and 42 present the data on labor requirements for Cases 1 and 2 respectively.

Phase	Parameter	Value	Unit	Source
(0) R&D – Deploy. of gen. II reactors (case of France, 1971-2002)	Cumulative installed capacity	63 130	MWe	CEA, 2009
	Direct workforce	5 600	man-year/y (av. For 1971-1997)	after Bataille and Galley, 1999
	Productivity	2 400	man-year/GWe	
(1) Mining	Productivity	80	t_{ORE}/man-year/y (av.)	after OECD/IAEA, 2004
(2) Enriching	Centrifuge	80	man-year/y	after Rothwell, 2009
	Fuel fabrication	40	man-year/y	after Rothwell, 2010
(3) Generating power	Construct.	14 360	man-year/GWe	NEI, 2010
	Operation	400	man-year/y	NEI, 2010
	Maint.	1 000	man-year/y	NEI, 2010
		30	days/y	
	Dismantling (35% of construct.)	5 000	man-year/GWe	Lenzen, 2008
(4) Handling waste	Waste storage and disposal of HLW	not included		
	Waste storage and disposal of ILW/LLW (case of France)	200	man-year/y	ANDRA, 2008
		43 000	$t_{ILW/LLW}$/y	ANDRA, 2008
		4.7	man-year/$kt_{ILW/LLW}$	after ANDRA, 2008
	Average working hours	1 800	h/y	OECD, 2008

Table 41: Data on labor requirements – Case 1

Phase	Parameter	Value	Unit	Source
(0) R&D – Deploy. of gen. II reactors (case of France, 1971-2002)	Cumulative installed capacity	63 130	MWe	CEA, 2009
	Direct workforce	5 600	man-year/y (av. For 1971-1997)	after Bataille and Galley, 1999
	Productivity	2 400	man-year/GWe	
(1) Mining	Productivity	80	t_{ORE}/man-year/y (av.)	after OECD/IAEA, 2004
(2) Enriching	Centrifuge	70	man-year/y	after Rothwell, 2009
	Fuel fabrication	30	man-year/y	after Rothwell, 2010
(3) Generating power and Reprocess.	Construct.	14 360	man-year/GWe	NEI, 2010
	Operation	400	man-year/y	NEI, 2010
	Maint.	1 000	man-year/y	NEI, 2010
		30	days/y	
	Dismantling (35% of construct.)	5 000	man-year/GWe	Lenzen, 2008
	French reproces. plant of La Hague	6 000	man-year/y	Schneider and Marignac, 2008
		1 700	t_{USED}/y	Schneider and Marignac, 2008
		3.5	man-year/t_{USED}	after Schneider and Marignac, 2008
(4) Handling waste	Waste storage and disposal of HLW	not included		
	Waste storage and disposal of ILW/LLW (case of France)	200	man-year/y	ANDRA, 2008
		43 000	$t_{ILW/LLW}$/y	ANDRA, 2008
		4.7	man-year/$kt_{ILW/LLW}$	after ANDRA, 2008
	Average working hours	1 800	h/y	OECD, 2008

Table 42: Data on labor requirements – Case 2

5.3.1.1 Direct labor requirements

Tables 43 and 44 present the specific direct labor requirements (flows) expressed in relation to the *net* electricity output for Cases 1 and 2 respectively.

Phase	Process	Value	Unit
(1) Mining	Mining, Milling and Conversion	367	h/GWh$_{el}$
(2) Enriching	Enriching and Fuel fabrication	25	h/GWh$_{el}$
(3) Generating power	Operation	83	h/GWh$_{el}$
(4) Handling waste	Waste storage and disposal	8.4	h/t$_{ILW/LLW}$
TOTAL		**480**	**h/GWh$_{el}$**

Table 43: Specific direct labor requirements (flows) – Case 1

Phase	Process	Value	Unit
(1) Mining	Mining, Milling and Conversion	309	h/GWh$_{el}$
(2) Enriching	Enriching and Fuel fabrication	21	h/GWh$_{el}$
(3) Generating power and Reprocess.	Operation	83	h/GWh$_{el}$
	Reception and storage Reprocess. Fuel fab. and Vitrification	6.4	h/t$_{USED}$
(4) Handling waste	Waste storage and disposal	8.4	h/t$_{ILW/LLW}$
TOTAL		**410**	**h/GWh$_{el}$**

Table 44: Specific direct labor requirements (flows) – Case 2

5.3.1.2 Indirect labor requirements

Tables 45 and 46 present the specific indirect labor requirements (funds) expressed in relation to the *net* electricity output—considering a plant lifetime of 40 years (Table 5)—for Cases 1 and 2 respectively.

Phase	Process	Value	Unit
(1) Mine	Mining, Milling and Conversion	not included	
(2) Enrich. plant	Enriching and Fuel fabrication	not included	
(3) Power plant	R&D	5.6	Mh
	Construct.	34	Mh
	Maint.	17	h/GWh$_{el}$
	Dismantling	12	Mh
(4) Waste facilities	Waste storage and disposal	not included	
TOTAL		**160**	**h/GWh$_{el}$**

Table 45: Specific indirect labor requirements (funds) – Case 1

Phase	Process	Value	Unit
(1) Mine	Mining, Milling and Conversion	not included	
(2) Enrich. plant	Enriching and Fuel fabrication	not included	
(3) Power plant and Reprocess. plant	R&D	5.6	Mh
	Construct.	34	Mh
	Maint.	17	h/GWh_{el}
	Dismantling	12	Mh
	Reception and storage Reprocess. Fuel fab. and Vitrification	not included	
(4) Waste facilities	Waste storage and disposal	not included	
TOTAL		**160**	**h/GWh_{el}**

Table 46: Specific indirect labor requirements (funds) – Case 2

5.3.2 Fossil energy

For the fossil energy system, only direct labor requirements (flows) have been considered. Indeed, indirect labor requirements for the making and maintenance of funds are considered negligible given the much lower fossil-fuel requirements of the fossil energy system compared to the nuclear energy system—even when considering an equivalent net electricity generated. Then, since there is a relation between the energy intensity and labor intensity when making and maintaining fund elements (mostly construction/dismantling efforts), this justifies the rationale of considering the indirect labor requirements of fossil energy being negligible in comparison with nuclear energy.

Moreover, the labor requirements for the operation process of the "Generating power" phase have been evaluated considering data from the US Census on the fossil-fuel electric power generation at the national level for the year 2002 (US Census Bureau, 2004).

Tables 47 and 48 present the data on labor requirements for Cases 3 and 4 respectively.

Phase	Parameter	Value	Unit	Source
(1) Mining and Refining	Productivity	14	t_{coal}/h (Surface)	Darmstadter, 1999
		5	t_{coal}/h (Underg.)	Darmstadter, 1999
		8	t_{coal}/h (av.)	
(2) Generating power – Fossil fuel electric power generation in the US in 2002	Number of plants	1 233		U.S. Census Bureau, 2004 – Table 1
	Number of employees	67 294		U.S. Census Bureau, 2004 – Table 1
		55	man-year/y (av.)	
(3) Handling waste		N/A		
	Average working hours	1 800	h/y	OECD, 2008

Table 47: Data on labor requirements – Case 3

Phase	Parameter	Value	Unit	Source
(1) Mining and Refining	Productivity	14	t_{coal}/h (Surface)	Darmstadter, 1999
		5	t_{coal}/h (Underg.)	Darmstadter, 1999
		8	t_{coal}/h (av.)	
(2) Generating power – Fossil fuel electric power generation in the US in 2002	Number of plants	1 233		U.S. Census Bureau, 2004 – Table 1
	Number of employees	67 294		U.S. Census Bureau, 2004 – Table 1
		55	man-year/y (av.)	
(3) Handling waste	Capture, Compress., Transport and Storage	not included		
	Average working hours	1 800	h/y	OECD, 2008

Table 48: Data on labor requirements – Case 4

Tables 49 and 50 present the specific direct labor requirements (flows) expressed in relation to the *net* electricity output for Cases 3 and 4 respectively.

Phase	Process	Value	Unit
(1) Mining and Refining	Mining and Cleaning	42	h/GWh_{el}
(2) Generating power	Operation	23	h/GWh_{el}
(3) Handling waste		N/A	
TOTAL		**65**	**h/GWh_{el}**

Table 49: Specific direct labor requirements (flows) – Case 3

Phase	Process	Value	Unit
(1) Mining and Refining	Mining and Cleaning	58	h/GWh_{el}
(2) Generating power	Operation	30	h/GWh_{el}
(3) Handling waste	Capture, Compress., Transport and Storage	not included	
TOTAL		**88**	**h/GWh_{el}**

Table 50: Specific direct labor requirements (flows) – Case 4

5.4 Material requirements

Only the indirect material requirements (funds) have been considered here given the fact that direct material requirements (flows) are relatively negligible. The data presented in this section only intend to provide orders of magnitude on the most common materials used in the making and maintenance of the funds (not to be confused with the natural resources—uranium and coal—that correspond to the PES): (i) concrete, (ii) steel and (iii) copper.

5.4.1 Nuclear energy

The material requirements for nuclear energy have been evaluated using Storm van Leeuwen and Smith's (2008) study for the “Power plant” and Lenzen's (2008) study for the “Waste facilities”.

Tables 51 and 52 present the indirect material requirements (funds) Cases 1 and 2 respectively.

Phase	Parameter	min	MAX	mean	Error	Unit	Source
(1) Mine				not included			
(2) Enrich. plant				not included			
(3) Power plant	Concrete	680 000	1 020 000	850 000	± 170 000	t	Storm van Leeuwen and Smith, 2008
	Reinforcing steel	75 800	113 700	95 300	± 18 400	t	Storm van Leeuwen and Smith, 2008
	Steel	43 600	65 400	54 700	± 10 700	t	Storm van Leeuwen and Smith, 2008
(4) Waste facilities	Concrete	-	-	117	-	m^3/t_{HLW}	after Lenzen, 2008
		-	-	0.56	-	$m^3/t_{ILW/LLW}$	after Lenzen, 2008
	Reinforcing steel	-	-	1.6	-	t/t_{HLW}	after Lenzen, 2008
	Steel	-	-	0.012	-	$t/t_{ILW/LLW}$	after Lenzen, 2008
	Copper	-	-	1.0	-	t/t_{HLW}	after Lenzen, 2008
	Density of concrete		2.5 t/m^3	*assumption*			
TOTAL	**Concrete**	-	-	**13 000**	**± 490**	**t/TWh_{el}**	
	Steel	-	-	**490**	**± 84**	**t/TWh_{el}**	
	Copper	-	-	**35**	**-**	**t/TWh_{el}**	

Table 51: Indirect material requirements (funds) – Case 1

Phase	Parameter	min	MAX	mean	Error	Unit	Source
(1) Mine				not included			
(2) Enrich. plant				not included			
(3) Power plant and Reprocess. plant	Concrete	680 000	1 020 000	850 000	± 170 000	t	Storm van Leeuwen and Smith, 2008
	Reinforcing steel	75 800	113 700	95 300	± 18 400	t	Storm van Leeuwen and Smith, 2008
	Steel	43 600	65 400	54 700	± 10 700	t	Storm van Leeuwen and Smith, 2008
	Reprocess. Plant			not included			
(4) Waste facilities	Concrete	-	-	117	-	m^3/t_{HLW}	after Lenzen, 2008
		-	-	0.56	-	$m^3/t_{ILW/LLW}$	after Lenzen, 2008
	Reinforcing steel	-	-	1.6	-	t/t_{HLW}	after Lenzen, 2008
	Steel	-	-	0.012	-	$t/t_{ILW/LLW}$	after Lenzen, 2008
	Copper	-	-	1.0	-	t/t_{HLW}	after Lenzen, 2008
	Density of concrete		2.5 t/m^3	*assumption*			
TOTAL	**Concrete**	-	-	**12 000**	**± 490**	**t/TWh_{el}**	
	Steel	-	-	**490**	**± 84**	**t/TWh_{el}**	
	Copper	-	-	**31**	**-**	**t/TWh_{el}**	

Table 52: Indirect material requirements (funds) – Case 2

5.4.2 Fossil energy

Tables 53 and 54 present the indirect material requirements (funds) Cases 3 and 4 respectively.

Phase	Parameter	Value	Unit	Source
(1) Mine, Refinery and Power plant	Concrete	62 600	m^3	Koornneef et al., 2008
	Steel	44 801	t	Koornneef et al., 2008
	Copper	710	t	Koornneef et al., 2008
(3) Waste facility		N/A		
	Density of concrete	2.5	t/m^3	*assumption*
TOTAL	**Concrete**	**1 200**	**t/TWh_{el}**	
	Steel	**360**	**t/TWh_{el}**	
	Copper	**5.6**	**t/TWh_{el}**	

Table 53: Indirect material requirements (funds) – Case 3

Phase	Parameter	Value	Unit	Source
(1) Mine, Refinery and Power plant	Concrete	62 600	m^3	Koornneef et al., 2008
	Steel	44 801	t	Koornneef et al., 2008
	Copper	710	t	Koornneef et al., 2008
(3) Waste facility – CCS	Concrete	22 462	m^3	after Koornneef et al., 2008
	Reinforcing steel	12 000	t	Koornneef et al., 2008
	Steel	415	t	after Koornneef et al., 2008
	Copper	432	t	after Koornneef et al., 2008
	Density of concrete	2.5	t/m^3	*assumption*
TOTAL	**Concrete**	**2 200**	**t/TWh_{el}**	
	Steel	**590**	**t/TWh_{el}**	
	Copper	**12**	**t/TWh_{el}**	

Table 54: Indirect material requirements (funds) – Case 4

5.5 Sensitivity analysis

The results shown in the previous sections can vary widely because of different factors. Indeed, it has been shown that the ore grade and the enrichment method are the parameters that influence the most the results for the nuclear energy system (Lenzen, 2008), while the mining method (surface vs. underground) appears to be a key factor given the difference of productivity between the two methods (Darmstadter, 1999).

As a result, three other calculations are performed for the sensitivity analysis considering the following scenarios:

1. A low value of uranium ore grade (0.045%) which represents the essential of the

reserves in Australia (sensitivity analysis on Cases 1 and 2).
There is a high variation of the uranium ore grades between the different mines around the world as shown by (Lenzen, 2008). The importance of the resource quality in the quality of energy sources has been demonstrated a long time ago in the case of fossil energy sources (e.g. Hall et al., 1986). According to Storm van Leeuwen and Smith ([30] in Lenzen, 2008), the relationship between natural resource quality (uranium ore grade) and energy intensity is exponential meaning that energy intensity increases more rapidly than ore grade decreases, the energy intensity being inversely proportional to the recovery rate. The authors also showed that the empirical extraction yield declines much more sharply than the hypothetical one. Figure 6 illustrates the increase in fossil-fuel requirements due to the variations of uranium ore grades.

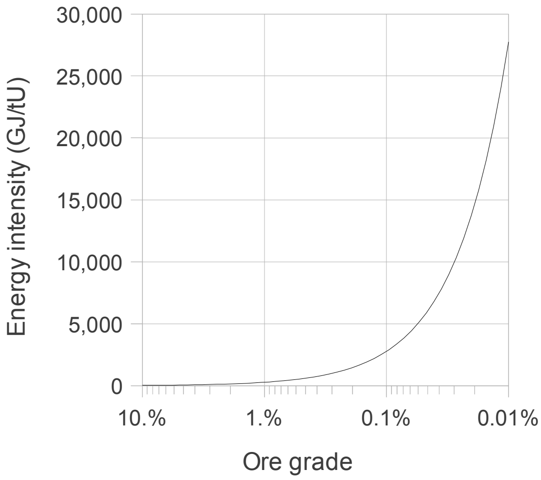

Figure 6: Specific fossil-fuel requirements for mining and milling vs. ore grade
(source: after Lenzen, 2008)

The baseline cases of this report have considered an average ore grade of 0.15%. Given the sharp variation shown in Figure 6, one can expect in return large variations on the biophysical requirements.

2. Enrichment process using the gas centrifuge method only (100%) which requires less electricity than the gaseous diffusion method.
   In the baseline cases, 30% of the enrichment has been considered using gaseous diffusion. However, this percentage is decreasing in favor of the centrifuge method which justifies the scenario considered in the sensitivity analysis.

3. Coal mining using the surface method only (100%) which entails a higher productivity than the underground mining method.
   In the baseline cases, only 40% of the mining have been considered performed at the surface. However, the trend in coal mining is to develop surface mining methods especially in developed countries such as in Germany. This scenario represents the hypothetical case where all coal mining would be performed at the surface. Note that surface mining demonstrates an energy intensity of the same order of magnitude as underground mining (Spath et al., 1999) so that indirect fossil-fuel requirements (funds) are not affected by this scenario.

Tables 55–58 present the results of the sensitivity analysis.

Variable	Scenario	Variation	Case	Electricity requ. – Flows (MWh_{el}/GWh_{el}*)			Electricity requ. – Funds (MWh_{el}/GWh_{el})		
				Mean	Error	*(Sensi-tivity)*	Mean	Error	*(Sensi-tivity)*
	Baseline cases		Case 1	33	± 0.4		not included	-	
			Case 2	34	± 0.4		not included	-	
			Case 3	3.2	-		0.32	-	
			Case 4	120	± 6		0.32	-	
Ore grade	Low (Australia)	0.045%	Case 1	33		*(0%)*	not included		-
			Case 2	34		*(0%)*	not included		-
Enrichment method	100% Centrifuge	1	Case 1	24		***-(30%)***	not included		-
			Case 2	25		***-(30%)***	not included		-
Mining method	100% Surface	1	Case 3	3.2		*(0%)*	0.32		*(0%)*
			Case 4	120		*(0%)*	0.32		*(0%)*

Table 55: Results of the sensitivity analysis – Electricity requirements
*: Values expressed in relation to the *gross* electricity output.

Variable	Scenario	Variation	Case	Fossil-fuel requ. – Flows (GJ/GWh_{el})			Fossil-fuel requ. – Funds (GJ/GWh_{el})		
				Mean	Error	*(Sensi-tivity)*	Mean	Error	*(Sensi-tivity)*
	Baseline cases		Case 1	250	± 130		110	± 9	
			Case 2	480	± 130		100	± 9	
			Case 3	160	-		2.3	-	
			Case 4	210	-		4.0	-	
Ore grade	Low (Australia)	0.045%	Case 1	310		***(20%)***	160		***(50%)***
			Case 2	520		***(10%)***	140		***(40%)***
Enrichment method	100% Centrifuge	1	Case 1	250		*(0%)*	110		*(0%)*
			Case 2	480		*(0%)*	100		*(0%)*
Mining method	100% Surface	1	Case 3	160		*(0%)*	2.3		*(0%)*
			Case 4	210		*(0%)*	4.0		*(0%)*

Table 56: Results of the sensitivity analysis – Fossil-fuel requirements

Variable	Scenario	Variation	Case	Labor requ. – Flows (h/GWh_{el})			Labor requ. – Funds (h/GWh_{el})		
				Mean	Error	*(Sensi-tivity)*	Mean	Error	*(Sensi-tivity)*
	Baseline cases		Case 1	480	-		160	-	
			Case 2	410	-		160	-	
			Case 3	65	-		not included	-	
			Case 4	87	-		not included	-	
Ore grade	Low (Australia)	0.045%	Case 1	1330		***(180%)***	160		*(0%)*
			Case 2	1130		***(180%)***	160		*(0%)*
Enrichment method	100% Centrifuge	1	Case 1	470		*(0%)*	160		*(0%)*
			Case 2	410		*(0%)*	160		*(0%)*
Mining method	100% Surface	1	Case 3	48		***-(30%)***	not included		-
			Case 4	65		***-(30%)***	not included		-

Table 57: Results of the sensitivity analysis – Labor requirements

Variable	Scenario	Variation	Case	Material requ. (concrete) – Funds (t/TWh$_{el}$)			Material requ. (steel) – Funds (t/TWh$_{el}$)			Material requ. (copper) – Funds (t/TWh$_{el}$)		
				Mean	Error	*(Sensi-tivity)*	Mean	Error	*(Sensi-tivity)*	Mean	Error	*(Sensi-tivity)*
	Baseline cases		Case 1	13 000	± 490		490	± 84		35	-	
			Case 2	12 000	± 490		490	± 84		31	-	
			Case 3	1 200	-		360	-		5.6	-	
			Case 4	2 200	-		590	-		12	-	
Ore grade	Low (Australia)	0.045%	Case 1	13 000		*(0%)*	490		*(0%)*	35		*(0%)*
			Case 2	12 000		*(0%)*	490		*(0%)*	31		*(0%)*
Enrichment method	100% Centrifuge	1	Case 1	13 000		*(0%)*	490		*(0%)*	34		*(0%)*
			Case 2	12 000		*(0%)*	480		*(0%)*	31		*(0%)*
Mining method	100% Surface	1	Case 3	1 200		*(0%)*	360		*(0%)*	5.6		*(0%)*
			Case 4	2 200		*(0%)*	590		*(0%)*	12		*(0%)*

Table 58: Results of the sensitivity analysis – Material requirements

6. Conclusion

The biophysical explanation proposed here is based on the use of a grammar capable of analyzing the process of production of electricity in modular elements, defined using semantic and formal categories. In this way it becomes possible to individuate similarities and differences in the process of production of electricity, and then measure and compare “apples” with “apples” and “oranges” with “oranges”.

The biophysical requirements of nuclear energy and fossil energy presented in this report make it possible to compare the performance of the two power-supply systems.

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Appendixes

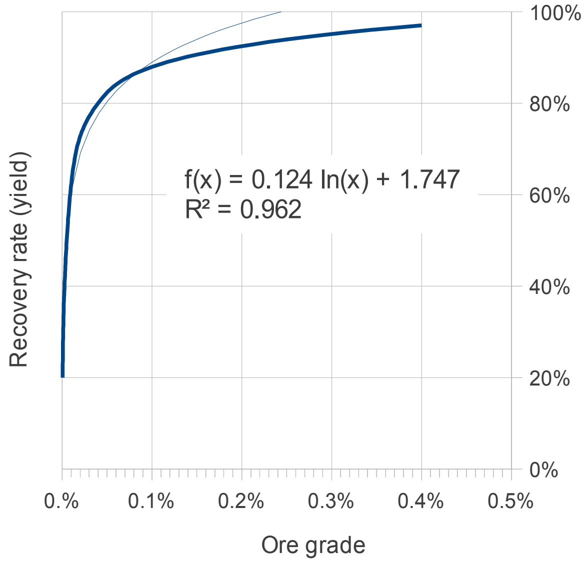

Figure A.1: Recovery rate (yield) vs. Ore grade
(source: after Lenzen, 2008)

Process parameters						
				Feed: **264** t_{UF6}		
Feed Assay	0.711% U-235	**Enrich. effort:**		|		**Product: (enriched)**
Product Assay	3.5% U-235	**120 000** SWU	→	Enrichment Plant	→	**38** t_{UF6}
Tails Assay	0.25% U-235			|		
				Tails: (depleted) **227** t_{UF6}		

Table A.1: Mass balance evaluation of uranium enrichment (Case 1)
(source: after WISE, 2009a)

Process parameters						
				Feed: **222** t_{UF6}		
Feed Assay	0.711% U-235	**Enrich. effort:**		|		**Product: (enriched)**
Product Assay	3.5% U-235	**101 000** SWU	→	Enrichment Plant	→	**32** t_{UF6}
Tails Assay	0.25% U-235			|		
				Tails: (depleted) **191** t_{UF6}		

Table A.2: Mass balance evaluation of uranium enrichment (Case 2)
(source: adapted from WISE, 2009a)

Plutonium recycled from spent fuel by reprocessing for use in mixed-oxide fuel (MOX)	Input: **460 kg_{Pu}/y** ***300 kg_{Puf}/y*** **6 t_{UO2}/y** ***5 t_U/y*** Output: **6 t_{MOX}/y** ***5 t_{HM}/y***
Enrichment of uranium recycled from spent fuel by reprocessing (U_{rep})	**Feed:** **0.3** $t_{UF6\ (rep)}$ | **Enrich. effort:** **190** SWU → Enrichment Plant → **Product: (enriched)** **0.04** t_{UF6} | **0.03** t_{UO2} **Tails: (depleted)** **0.3** t_{UF6} ***0.03*** *t_U*
Re-enrichment of depleted uranium (U_{dep})	**Feed:** **190** $t_{UF6\ (dep)}$ | **Enrich. effort:** **17 200** SWU → Enrichment Plant → **Product: (enriched)** **5** t_{UF6} | **4** t_{UO2} **Tails: (depleted)** **160** t_{UF6} ***4*** *t_U*

Table A.3: Mass balance evaluation for the reprocessing phase (Case 2)
(source: WISE, 2009b)

Country	Production Employment (pers/y)	Production (tU/y)	Average grade (%-U3O8)
Brazil	128	272	0.108
Canada	972	11607	17.584
Kazakhstan	1280	2822	0.065
Namibia	782	2333	0.030
Niger	1348	3080	0.412
Russian Federation	5000	2850	0.188
Productivity	**2.41 (tU/pers)**		**3.06% (U3O8)**

Table A.4: Uranium mining productivity (Cases 1 and 2)
(source: after OECD/IAEA, 2004)